Biopower

Technology Description

Biopower, also called biomass power, is the generation of electric power from biomass resources – now usually urban waste wood, crop and forest residues; and, in the future, crops grown specifically for energy production. Biopower reduces most emissions (including emissions of greenhouse gases-GHGs) compared with fossil fuel-based electricity. Since biomass absorbs CO_2 as it grows, the entire biopower cycle of growing, converting to electricity, and regrowing biomass can result in very low CO_2 emissions. Through the use of residues, biopower systems can even represent a net sink for GHG emissions by avoiding methane emissions that would result from landfilling of the unused biomass.

Representative Technologies for Conversion of Feedstock to Fuel for Power and Heat

• *Homogenization* is a process by which feedstock is made physically uniform for further processing or for combustion. (includes chopping, grinding, baling, cubing, and pelletizing)

• *Gasification* (via pyrolysis, partial oxidation, or steam reforming) converts biomass to a fuel gas that can be substituted for natural gas in combustion turbines or reformed into H_2 for fuel cell applications.

• *Anaerobic digestion* produces biogas that can be used in standard or combined heat and power (CHP) applications. Agricultural digester systems use animal or agricultural waste. Landfill gas also is produced anaerobically.

• *Biofuels production for power and heat* provides liquid-based fuels such as methanol, ethanol, hydrogen, or biodiesel.

Representative Technologies for Conversion of Fuel to Power and Heat

• Direct combustion systems burn biomass fuel in a boiler to produce steam that is expanded in a Rankine Cycle prime mover to produce power.

• Cofiring substitutes biomass for coal or other fossil fuels in existing coal-fired boilers.

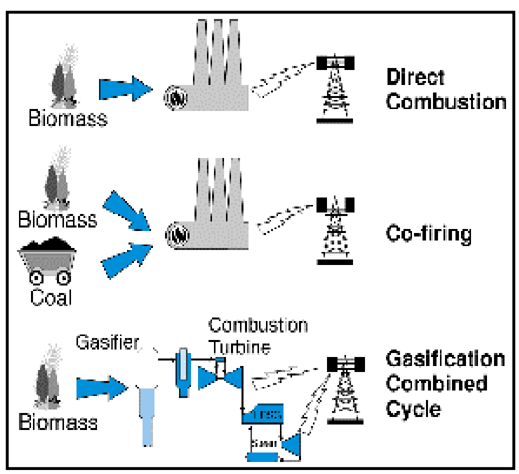
• Biomass or biomass-derived fuels (e.g. syngas, ethanol, biodiesel) also can be burned in combustion turbines (Brayton cycle) or engines (Otto or Diesel cycle) to produce power.

• When further processed, biomass-derived fuels can be used by fuels cells to produce electricity

System Concepts

• CHP applications involve recovery of heat for steam and/or hot water for district energy, industrial processes, and other applications.

• Nearly all current biopower generation is based on **direct combustion** in small, biomass-only plants with relatively low electric efficiency (20%), although total system efficiencies for CHP can approach 90%. Most biomass direct-combustion generation facilities utilize the basic Rankine cycle for electric power generation, which is made up of the steam generator (boiler), turbine, condenser, and pump.



• For the near-term, **cofiring** is the most cost-effective of the power-only technologies. Large coal steam plants have electric efficiencies near 33%. The highest levels of coal cofiring (15% on a heat input basis) require separate feed preparation and injection systems.

• Biomass **gasification combined cycle** plants promise comparable or higher electric efficiencies (> 40%) using only biomass because they involve gas turbines (Brayton cycle), which are more efficient than Rankine cycles. Other technologies being developed include integrated gasification/fuel cell and biorefinery concepts.

Technology Applications

• The existing biopower sector, nearly 1,000 plants, is mainly comprised of direct-combustion plants, with an additional small amount of cofiring (six operating plants). Plant size averages 20 MW_e, and the biomass-to-electricity conversion efficiency is about 20%. Grid-connected electrical capacity has increased from less than 200 MW_e in 1978 to over 6500 MW_e in 2000. More than 75% of this power is generated in the forest products industry's CHP applications for process heat. Wood-fired systems account for close to 95% of this capacity. In addition, about 3,300 MW_e of municipal solid waste and landfill gas generating capacity exists. Recent studies estimate that on a life-cycle basis, existing biopower plants represent an annual net carbon sink of 4 MMTCe. Prices generally range from 8 to 12¢/kWh.

Current Status

• CHP applications using a waste fuel are generally the most cost-effective biopower option. Growth is limited by availability of waste fuel and heat demand.
• Biomass cofiring with coal ($50 - 250/kW of biomass capacity) is the most near-term option for large-scale use of biomass for power-only electricity generation. Cofiring also reduces sulfur dioxide and nitrogen oxide emissions. In addition, when cofiring crop and forest product residues, GHG emissions are reduced by a greater percentage (e.g. 23% GHG emissions reduction with 15% cofiring).
• Biomass gasification for large-scale (20 - 100MW_e) power production is being commercialized. It will be an important technology for cogeneration in the forest products industries (which project a need for biomass and black liquor CHP technologies with a higher electric thermal ratio), as well as for new baseload capacity. Gasification also is important as a potential platform for a biorefinery.
• Small biopower and biodiesel systems have been used for many years in the developing world for electricity generation. However, these systems have not always been reliable and clean. DOE is developing systems for village power applications and for developed world distributed generation that are efficient, reliable, and clean. These systems range in size from 3kW to 5MW and will begin field verification in the next 1-3 years.
• Current companies include:

Future Energy Resources, Inc. (FERCO)	Foster Wheeler
Energy Products of Idaho	PRM Energy Systems

Technology History

• In the latter part of the 19th century, wood was the primary fuel for residential, commercial, and transportation uses. By the 1950s, other fuels had supplanted wood. In 1973, wood use had dropped to 50 million tons per year.
• At that point, the forest products and pulp and paper industries began to use wood with coal in new plants and switched to wood-fired steam power generation.
• The Public Utility Regulatory Policies Act (PURPA) of 1978 stimulated the development of nonutility cogeneration and small-scale plants, leading to 70% self-sufficiency in the wood processing and pulp-and-paper sectors.
• As incentives were withdrawn in the late 1980s, annual installations declined from just over 600 MW in 1989, to 300-350MW in 1990.
• There are now nearly 1,000 wood-fired plants in the United States, with about two-thirds of those providing power (and heat) for on-site uses only.

Technology Future

The levelized cost of electricity (in constant 1997$/kWh) for Biomass Direct-fired and Gasification configurations are projected to be:

	2000	2010	2020
Direct-fired	7.5	7.0	5.8
Gasification	6.7	6.1	5.4

Source: *Renewable Energy Technology Characterizations*, EPRI TR-109496.

- R&D Directions include:

Gasification – This technology requires extensive field verification in order to be adopted by the relatively conservative utility and forest products industries, especially to demonstrate integrated operation of biomass gasifier with advanced power generation (turbines and/or fuel cells). Integration of gasification into a Biorefinery platform is a key new research area.

Small Modular Systems – Small-scale systems for distributed or minigrid (for premium or village power) applications will be increasingly in demand.

Cofiring – The DOE biopower program is moving away from research on cofiring, as this technology has reached a mature status. However, continued industry research and field verifications are needed to address specific technical and nontechnical barriers to cofiring. Future technology development will benefit from finding ways to better prepare, inject, and control biomass combustion in a coal-fired boiler. Improved methods for combining coal and biomass fuels will maximize efficiency and minimize emissions. Systems are expected to include biomass cofiring up to 5% of natural gas combined cycle capacity.

Biomass

Market Data

Cumulative Generating Capability, by Type (MW)	Source: *Energy Information Administration, Annual Energy Outlooks for 1998-2002, Table A17, and Renewable Resources in the U.S. Electricity Supply, 1993, Table 4, and world data from United Nations Development Program, World Energy Assessment, 2000, Table 7.25.*								
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
U.S. Electric Generators									
Municipal Solid Waste*				2,870	3,410	2,490	2,560	2,750	2,840
Wood and Other Biomass				1,910	1,640	1,760	1,460	1,370	1,390
U.S. Cogenerators									
Municipal Solid Waste*				410	460	520	700	510	510
Wood and Other Biomass				5,350	5,450	6,000	4,640	5,260	5,260
U.S. Total									
Municipal Solid Waste*			2,000	3,280	3,870	3,010	3,260	3,260	3,350
Wood and Other Biomass			6,000	7,260	7,090	7,760	6,100	6,630	6,650
Biomass Total			8,000	10,540	10,960	10,770	9,360	9,890	10,000
Rest of World Total**							30,000		
World Total							40,000		

* Municipal Solid Waste includes Landfill Gas

** Number derived from subtracting U.S. total from the world total. Figures may not add due to rounding.

U.S. Annual Installed Generating Capability, by Type (MW)	Source: *Renewable Electric Plant Information System (REPiS), Version 5, NREL, 2001.*								
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Agricultural Waste[1]	22.6	20.1		4.0		21.6			
Biogas[2]	0.1	55.6	49.8	17.5	73.2	95.6	91.1	107.6	
Municipal Solid Waste[3]	50.0	117.2	260.3	94.5				22.0	
Wood Residues[4]	260.4	255.4	347.9	66.5	91.6	40.0	90.3	13.0	
Total	333.0	448.3	658.0	182.5	164.8	157.2	181.4	142.6	

U.S. Cumulative Generating Capability, by Type* (MW)	Source: *Renewable Electric Plant Information System (REPiS), Version 5, NREL, 2001.*								
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Agricultural Waste[1]	40	92	165	351	351	373	373	373	
Biogas[2]	18	114	356	522	595	691	782	889	
Municipal Solid Waste[3]	263	697	2,172	2,916	2,916	2,916	2,916	2,938	
Wood Residues[4]	3,576	4,935	6,371	7,317	7,409	7,449	7,539	7,552	
Total	3,897	5,837	9,064	11,106	11,270	11,428	11,609	11,752	

* There are an additional 65.45 MW of Ag Waste, .945 MW of Bio Gas, 32.1 MW of MSW and 483.31 MW of Wood Residues that are not accounted for here because they have no specific online date.

[1]Agricultural residues, cannery wastes, nut hulls, fruit pits, nut shells

[2]Biogas, alcohol (includes butahol, ethanol, and methanol), bagasse, hydrogen, landfill gas, livestock manure, wood gas (from wood gasifier)

[3]Municipal solid waste (includes industrial and medical), hazardous waste, scrap tires, wastewater sludge, refused-derived fuel

[4]Timber and logging residues (Includes tree bark, wood chips, saw dust, pulping liquor, peat, tree pitch, wood or wood waste)

Generation from Cumulative Capacity, by Type (Billion kWh)	Source: *Energy Information Administration, Annual Energy Outlooks for 1998-2002, Table A17, and Renewable Resources in the U.S. Electricity Supply, 1993, Table 4, and world data from United Nations Development Program, World Energy Assessment, 2000, Table 7.25.*								
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
U.S. Electric Generators									
Municipal Solid Waste*				18.7	14.2	17.7	18.9	18.0	20.2
Wood and Other Biomass				7.1	4.3	6.9	6.5	7.5	8.4
U.S. Cogenerators									
Municipal Solid Waste*				2.0	1.8	3.0	3.9	3.2	3.3
Wood and Other Biomass				34.9	32.7	37.1	27.2	30.0	29.6
U.S. Total									
Municipal Solid Waste*			10.0	20.7	16.0	20.7	22.8	21.2	23.4
Wood and Other Biomass			31.0	42.0	37.0	44.0	33.7	37.5	38.0
Biomass Total			41.0	62.7	53.0	64.7	56.4	58.7	61.4
Rest of World Total**							104		
World Total							160		

* Municipal Solid Waste includes Landfill Gas

** Number derived from subtracting U.S. total from the world total. Figures may not add due to rounding.

U.S. Generation from Cumulative Capacity, by Type (Billion kWh)	Source: *Energy Information Administration, Monthly Energy Review, January 2002, Table 7.2.*								
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Waste**			13.2	20.3	20.7	20.6	21.3	27.1	24.6
Wood*			30.4	36.4	36.8	34.2	31.8	37.6	39.5
Total Biomass			43.6	56.7	57.5	54.8	53.1	64.7	64.1

* Wood includes wood, wood waste, black liquor, red liquor, spent sulfite liquor, wood sludge, peat, railroad ties, and utility poles.

** Waste includes Municipal solid waste, landfill gas, meathane, digester gas, liquid acetonitrile waste, tall oil, waste alcohol, medical waste, paper pellets, sludge waste, solid byproducts, tires, agricultural byproducts, closed loop biomass, fish oil

U.S. Annual Energy Consumption for Electricity Generation (Quadrillion Btu)	Source: *Energy Information Administration, Renewable Energy Annual 2000 (1995-1999), Table 3, and Energy Information Administration, Renewable Energy Annual 1995 (1990), Table 3.*								
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Industrial Sector				0.567	0.574	0.547	0.528	0.576	
Electric Utility Sector				0.017	0.020	0.021	0.021	0.021	
Electric Power Industry				0.584	0.594	0.567	0.548	0.596	
Total				1.168	1.188	1.135	1.097	1.193	

Technology Performance

Source: Renewable Energy Technology Characterizations, EPRI TR-109496, 1997 (this document is currently being updated by DOE and the values most likely will change).

Efficiency		**1980**	**1990**	**1995***	**2000**	**2005**	**2010**	**2015****	**2020**
Capacity Factor (%)	Direct Fired			80.0	80.0	80.0	80.0	80.0	80.0
	Co-Fired			85.0	85.0	85.0	85.0	85.0	85.0
	Gasification			80.0	80.0	80.0	80.0	80.0	80.0
Efficiency (%)	Direct Fired			23.0	27.7	27.7	27.7	30.8	33.9
	Co-Fired			32.7	32.5	32.5	32.5	32.5	32.5
	Gasification			36.0	36.0	37.0	37.0	39.3	41.5
Net Heat Rate (kJ/kWh)	Direct Fired			15,280	13,000	13,000	13,000	11,810	10,620
	Co-Fired			11,015	11,066	11,066	11,066	11,066	11,066
	Gasification			10,000	10,000	9,730	9,730	9,200	8,670

Cost		**1980**	**1990**	**1995***	**2000**	**2005**	**2010**	**2015**	**2020**
Total Capital Cost ($/kW)	Direct Fired			1,965	1,745	1,510	1,346	1,231	1,115
	Co-Fired***			272	256	241	230	224	217
	Gasification			2,102	1,892	1,650	1,464	1,361	1,258
Feed Cost ($/GJ)	Direct Fired			2.50	2.50	2.50	2.50	2.50	2.50
	Co-Fired***			-0.73	-0.73	-0.73	-0.73	-0.73	-0.73
	Gasification			2.50	2.50	2.50	2.50	2.50	2.50
Fixed Operating Cost ($/kW-yr)	Direct Fired			73.0	60.0	60.0	60.0	54.5	49.0
	Co-Fired***			10.4	10.1	9.8	9.6	9.5	9.3
	Gasification			68.7	43.4	43.4	43.4	43.4	43.4

		1980	1990	1995*	2000	2005	2010	2015	2020
Variable Operating Costs ($/kWh)	Direct Fired			0.009	0.007	0.007	0.007	0.006	0.006
	Co-Fired***			-0.002	-0.002	-0.002	-0.002	-0.002	-0.002
	Gasification			0.004	0.004	0.004	0.004	0.004	0.004
Total Operating Costs ($/kWh)	Direct Fired			0.055	0.047	0.047	0.047	0.043	0.039
	Co-Fired***			-0.008	-0.008	-0.008	-0.009	-0.009	-0.009
	Gasification			0.040	0.036	0.036	0.036	0.034	0.033
Levelized Cost of Energy ($/kWh)	Direct Fired			0.087	0.075		0.070		0.058
	Co-Fired***			N/A	N/A	N/A	N/A	N/A	N/A
	Gasification			0.073	0.067		0.061		0.054

* Data is for 1997, the base year of the Renewable Energy Technology Characterizations analysis.

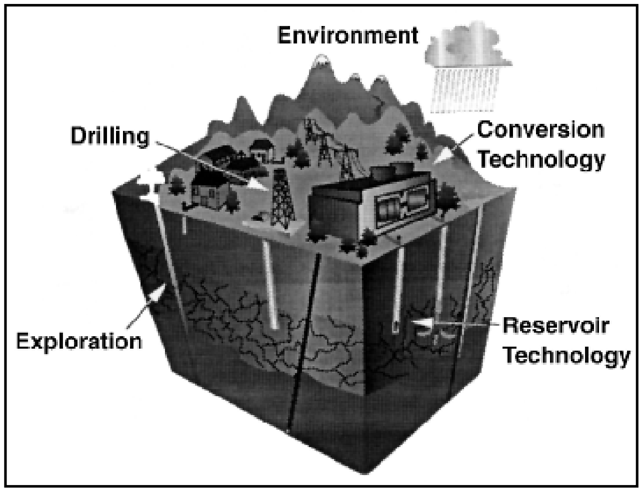
** Number derived by interpolation.

*** Note Co-Fired cost characteristics represent only the biomass portion of costs for capital and incremental costs above conventional costs for Operations & Maintenance (O&M), and assume $9.14/dry tonne biomass and $39.09/tonne coal, a Heat input from biomass at 19,104 kJ/kg, and that variable O&M includes an SO2 credit valued at $110/tonne SO2. No Co-firing COE is reported in the *RETC*.

Geothermal Energy

Technology Description

Geothermal energy is thermal energy from within the earth. Hot water and steam are used to produce electricity or applied directly for space heating and industrial processes. There is potential to use geothermal energy to recover minerals and metals present in the geothermal brine.



System Concepts

- Geophysical, geochemical, and geological exploration locate permeable hot reservoirs to drill.
- Wells are drilled into the reservoirs.
- Well fields and distribution systems allow the hot geothermal fluids to move to the point of use, and are injected back to the earth.
- Steam turbines using natural steam or hot water flashed to steam, and binary turbines produce mechanical power that is converted to electricity.
- Direct applications utilize the thermal energy directly, for heating, without conversion to another form of energy.

Representative Technologies

- Dry steam plants, which use geothermal steam to spin turbines;
- Flash steam plants, which pump deep, high-pressure hot water into lower-pressure tanks and use the resulting flashed steam to drive turbines.
- Binary-cycle plants, which use moderately hot geothermal water to heat a secondary fluid with a much lower boiling point than water. This causes the secondary fluid to flash to vapor, which then drives the turbines.
- Exploration technologies for the identification of fractures and geothermal reservoirs; drilling to access the resource; geoscience and reservoir testing and modeling to optimize production and predict useful reservoir lifetime.

Technology Applications

- Mile-or-more-deep wells can be drilled into underground reservoirs to tap steam and very hot water that drive turbines and electricity generators. Because of economies of scale, geothermal power plants supply power directly to the grid, typically operating as baseload plants.
- Another use is direct applications to use the heat from geothermal fluids without conversion to electricity. In the United States, most geothermal reservoirs are located in the western states, Alaska, and Hawaii, but some eastern states have geothermal resources that are used for direct applications. Hot water near Earth's surface can be piped directly into facilities and used to heat buildings, grow plants in greenhouses, dehydrate onions and garlic, heat water for fish farming, and pasteurize milk. Some cities pipe the hot water under roads and sidewalks to melt snow. District heating systems use networks of piped hot water to heat many buildings in a community.
- The recovery of minerals and metals from geothermal brine can add value to geothermal power projects

Current Status

- Hydrothermal reservoirs provide the heat for about 2100 MW of operating generating capacity in the United States at 18 resource sites. Another 700 MW of capacity at The Geysers has been shut down.
- Three types of power plants are operating today: Dry steam, flash steam, and binary.
- Worldwide installed capacity stands at about 8000 MW.
- The United States has a resource base capable of supplying heat for 40 GW of electrical capacity at costs competitive with conventional systems.
- Hydrothermal reservoirs are being used to produce electricity with an online availability of 97%; advanced energy conversion technologies are being implemented to improve plant thermal efficiency.
- Direct applications capacity is about 600 MW_t in the United States.
- Direct-use applications are successful, but require colocation of a quality heat source and need.
- More than 20 states utilize the direct use of geothermal energy, including Georgia and New York.
- Current leading geothermal technology companies include the following:

Calpine Corporation
Caithness Energy
Cal Energy Company (a subsidiary of Mid American Energy Holding Company)
Ormat International, Inc.

Technology History

- The use of geothermal energy as a source of hot water for spas dates back thousands of years.
- In 1892, the world's first district heating system was built in Boise, Idaho, as water was piped from hot springs to town buildings. Within a few years, the system was serving 200 homes and 40 downtown businesses. Today, the Boise district heating system continues to flourish. Although no one imitated this system for some 70 years, there are now 17 district heating systems in the United States and dozens more around the world.
- United States' first geothermal power plant went into operation in 1922 at The Geysers in California. The plant was 250 kW, but fell into disuse.
- In 1960, the country's first large-scale geothermal electricity-generating plant began operation. Pacific Gas and Electric operated the plant, located at The Geysers. The resource at the Geysers is dry steam. The first turbine produces 11 megawatts (MW) of net power and operated successfully for more than 30 years.
- In 1979, the first electrical development of a water-dominated geothermal resource occurred at the East Mesa field in the Imperial Valley in California.
- In 1980, UNOCAL built the country's first flash plant, generating 10 MW at Brawley, California.
- In 1981, with a supporting loan from DOE, Ormat International, Inc., successfully demonstrated binary technology in the Imperial Valley of California. This project established the technical feasibility of larger-scale commercial binary power plants. The project was so successful that Ormat repaid the loan within a year.
- By the mid 1980s, electricity was being generated by geothermal power in four western states: California, Hawaii, Utah, and Nevada.
- In the 1990s, the U.S. geothermal industry focused its attention on building power plants overseas, with major projects in Indonesia and the Philippines.
- In 1997, a pipeline began delivering treated municipal wastewater and lake water to The Geysers steamfield in California, increasing the operating capacity by 70 MW.
- In 2000, DOE initiated its GeoPowering the West program to encourage development of geothermal resources in the western United States by reducing nontechnical barriers.

Technology Future

The levelized cost of electricity (in constant 1997$/kWh) for the two major future geothermal energy configurations are projected to be:

	2000	2010	2020
Hydrothermal Flash	3.0	2.4	2.1
Hydrothermal Binary	3.6	2.9	2.7

Source: *Renewable Energy Technology Characterizations*, EPRI TR-109496.

- New approaches to utilization will be developed, which increase the domestic resource base by a factor of 10.
- Improved methodologies will be developed for predicting reservoir performance and lifetime.
- Advances will be made in finding and characterizing underground permeability and developing low-cost, innovative drilling technologies.
- Further R&D will reduce capital and operating costs and improve the efficiency of geothermal conversion systems.
- Heat recovery methods will be developed that allow the use of geothermal areas that are deeper, less permeable, or dryer than those currently considered as resources.

Geothermal

Market Data

Annual Installed Electric Capacity (MW_e)	Source: *Renewable Energy Project Information System (REPiS), Version 5, NREL, 2001.*								
	1980	1985	1990	1995	1996	1997	1998	1999	2000
U.S.	251.0	352.9	48.6		36.0				49.0
Rest of World									
World Total									

Cumulative Installed Electric Capacity (MW_e)	Source: Renewable Energy Project Information System (REPiS), Version 5, NREL, 2001, and *Renewable Energy World*/July-August 2000 page 123 Table 1.								
	1980	1985	1990	1995	1996	1997	1998	1999	2000
U.S.	802	1,698	2,540	2,684	2,720	2,720	2,720	2,720	2,769
Rest of World	1,298	3,066	3,293	4,114					5,206
World Total	2,100	4,764	5,832	6,797					7,974

Annual Generation from Cumulative Installed Electric Capacity (billion kWh)	Source: EIA,REA 2000- Table 4 (1995-99), EIA REA 1995 (1990) and, Renewable Energy World/July-August 2000 page 126, Table 2.								
	1980	1985	1990	1995	1996	1997	1998	1999	2000
U.S.									
Electric Power Industry			15.5	14.4	15.1	14.6	14.7	16.8	
Imports			0.58	0.88	0.65	0.02	0.05	0.03	
Electric Geothermal Total			16.1	15.2	15.8	14.6	14.8	16.8	
Rest of World									
World Total	14	17	19.0	20.0					49.3

Annual U.S. Geothermal Heat Pump Shipments, by type (units)	Source: Energy Information Administration - REA 2000- Table 35.								
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
ARI-320				4,696	4,697	7,772	10,510	13,236	
ARI-325/330				26,800	25,697	28,335	26,042	34,271	
Other non-ARI Rated				838	991	1,327	1,714	1,655	
Totals				32,334	31,385	37,434	38,266	49,162	

Capacity of U.S. Heat Pump Shipments* (Rated Tons)	Source: Energy Information Administration - REA 2000- Table 36.								
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
ARI-320				13,120	15,060	24,708	35,776	33,163	
ARI-325/330				113,925	92,819	110,186	98,912	149,303	
Other non-ARI Rated				3,935	5,091	6,662	6,758	6,070	
Totals				130,980	112,970	141,556	141,446	188,536	

* One Rated Ton of Capacity equals 12,000 Btu's.

Annual U.S. Geothermal Heat Pump Shipments by Customer Type and Model Type (units)	Source: *Energy Information Administration - REA 2000- Table 38, REA 1999- Table 38, and REA 1998- Table 40.*								
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Exporter					2,276	226	109	6,172	
Whole Sale Distributor					21,444	29,181	14,377	9,193	
Retail Distributor					8,336	829	3,222	2,555	
Installer					18,762	25,302	18,429	24,917	
End-User					689	657	994	66	
Others					13	1,727	1,135	6,259	
Total					51,520	57,922	38,266	49,162	

Annual U.S. Geothermal Heat Pump Shipments by Export & Census Region (units)

Source: *Energy Information Administration - REA 2000- Table 37, REA 1999- Table 37, and REA 1998- Table 39.*

	1980	1985	1990	1995	1996	1997	1998	1999	2000
Export					4,090	2,427	481	6,303	
Midwest					11,874	13,402	12,240	13,112	
Northeast					6,417	9,280	5,403	6,044	
South					25,302	26,788	16,195	20,935	
West					3,837	6,025	3,947	2,768	
Total					51,520	57,922	38,266	49,162	

Cumulative Installed Capacity

Source: *EIA - AEO 1997-2002, Table A17, Renewable Resources in the U.S. Electric Supply, 1993- Table 4, World Totals from UNDP World Energy Assessment 2000, Tables 7.20 and 7.22 and, Renewable Energy World/July-August 2000.*

	1980	1985	1990	1995	1996	1997	1998	1999	2000
Electricity (MW_e)									
U.S.			2,575	3,020	3,000	2,870	2,860	2,790	2,850
Rest of World			3,292	3,778		5,130	5,379		
World Total			5,867	6,798		8,000	8,239		
Direct Use- Heat (MW_{th})									
U.S.							1,910		
Rest of World							9,090		
World Total	1,950	7,072	8,064	8,664		10,400	11,000		17,175

Annual Generation from Cumulative Installed Capacity

Source: *EIA - AEO 1997-2002, Table A17, Renewable Resources in the U.S. Electric Supply, 1993- Table 4, and World Totals from UNDP World Energy Assesment 2000, Tables 7.20 and 7.22.*

	1980	1985	1990	1995	1996	1997	1998	1999	2000
Electricity (Billion kWh_e)									
U.S.			15.0	14.7	15.4	14.6	15.1	15.4	13.5
Rest of World						29.2	30.9		
World Total						43.8	46.0		
Direct Use- Heat (billion kWh_{th})									
U.S.							4.0		
Rest of World							36.0		
World Total		24.0		31.3		38.2	40.0		51.4

Installed Capacity and Power Generation/Energy Production from Installed Capacity

Source: *Lund and Freeston, World-Wide Direct Uses of Geothermal Energy 2000, Lund and Boyd, Geothermal Direct-Use in the United States Update: 1995-1999, J. Lund, World Status of Geothermal Energy Use Overview 1995-1999, Sifford and Blommquist, Geothermal Electric Power Production in the United States: A Survey and Update for 1995-1999, and G. Huttrer, The Status of World Geothermal Power Generation 1995-2000. Proceedings of the World Geothermal Congress 2000, Kyushu-Tohoku, Japan, May 28- June10, 2000.*

Cumulative Installed Capacity

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Electricity (MW_e)									
U.S.				2,369	2,343	2,314	2,284	2,293	2,228
Rest of World				4,464					5,746
World Total	3,887	4,764	5,832	6,833					7,974
Direct Use- Heat* (MW_{th})									
U.S.									4,200
Rest of World									12,975
World Total	1,950	7,072	8,064	8,664				16,209	17,175

Annual Generation/Energy Production from Cumulative Installed Capacity

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Electricity (Billion kWh_e)									
U.S.				14.4	15.1	14.6	14.7	15.0	15.5
Rest of World									33.8
World Total									49.3
Direct Use- Heat* (TJ)									
U.S.				13,890				20,302	21,700
Rest of World				98,551				141,707	
World Total		86,249		112,441				162,009	185,139

* Direct Use- Heat includes geothermal heat pumps as well as traditional uses. Geothermal Heat pumps account for 1854 MW_{th} (14,617 TJ) in 1995 and 6849 MW_{th} (23,214 TJ) in 1999 of the world totals and 3600 MW_{th} (8,800 TJ) in 2000 of the US total. Conversion of GWh to TJ is done at 1TJ = 0.2778 GWh.

Annual Generation from Cumulative Installed Capacity (Billion kWh)	Source: *EIA, Monthly Energy Review, December 2001- Table 7.2 Electricity Net Generation.*								
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
U.S.	5.1	9.3	15.8	14.4	15.1	14.6	14.7	15.0	14.2
Rest of World									
World Total									

Annual Geothermal Energy Consumption for Electric Generation (Quadrillion Btu)	Source: *EIA, Monthly Energy Review, Electric Power Sector Energy Consumption 1973-2000, http://tonto.eia.doe.gov/mer/.*								
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
U.S. Total	0.11	0.198	0.344	0.319	0.331	0.306	0.31	0.316	0.298
Rest of the World									
World Tota									

Annual Geothermal Energy Consumption (Quadrillion Btu)	Source: *EIA, Monthly Energy Review, Energy Consumption by Source 1973-2000, http://tonto.eia.doe.gov/mer/.*								
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
U.S. Total	0.11	0.198	0.355	0.333	0.346	0.322	0.328	0.335	0.319
Rest of the World									
World Tota									

Technology Performance

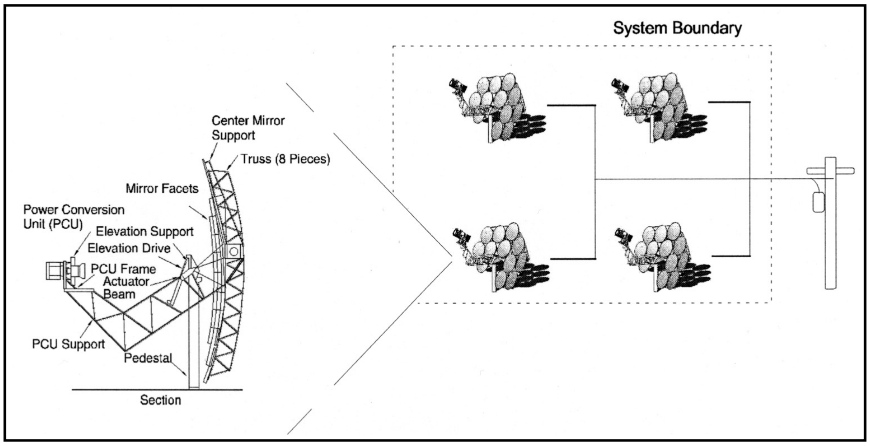
		1980	1990	1995	2000	2005	2010	2015	2020
Efficiency	Source: Renewable Energy Technology Characterizations, EPRI TR-109496, 1997 (this document is currently being updated by DOE and the values most likely will change).								
		1980	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
Capacity Factor (%)	Flashed Steam			89	92	93	95	96	96
	Binary			89	92	93	95	96	96
	Hot Dry Rock			80	81	82	83	84	85
Cost									
		1980	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
Capital Cost ($/kW)	Flashed Steam			1,444	1,372	1,250	1,194	1,147	1,100
	Binary			2,112	1,994	1,875	1,754	1,696	1,637
	Hot Dry Rock			5,519	5,176	4,756	4,312	3,794	3,276
Fixed O&M ($/kW-yr)	Flashed Steam			96.4	87.1	74.8	66.3	62.25	58.2
	Binary			87.4	78.5	66.8	59.5	55.95	52.4
	Hot Dry Rock			219	207	191	179	171	163

Concentrating Solar Power

Technology Description

Concentrating Solar Power (CSP) systems concentrate solar energy 50 to 5,000 times to produce high-temperature thermal energy, which is used to produce electricity for distributed or bulk generation power applications.

System Concepts



- In CSP systems, highly reflective sun-tracking mirrors produce temperatures of 400 to 800EC in the working fluid of a receiver; this heat is used in conventional heat engines (steam or gas turbines or Stirling engines) to produce electricity at system solar-to-electric efficiencies of up to 30%. Systems using advanced photovoltaics (PV) cells may achieve efficiencies greater than 35%.

Representative Technologies

- A parabolic trough system focuses solar energy on a linear oil-filled receiver, which collects heat to generate steam and power a steam turbine. When the sun is not shining, steam can be generated with fossil fuel to meet utility needs. Plant sizes can range from 10 to 100 MWe.
- A power tower system uses many large heliostats to focus the solar energy onto a tower-mounted central receiver filled with a molten-salt working fluid that produces steam. The hot salt can be stored efficiently to allow power production to match utility demand even when the sun is not shining. Plant size can range from 30 to 200 MWe.
- A dish/engine system (see diagram above) uses a dish-shaped reflector to power a small Stirling or Brayton engine/generator or a high-concentrator PV module mounted at the focus of the dish. Dishes are 2 to 25 kW in size, can be used individually or in small groups, and are easily hybridized with fossil fuel.

Technology Applications

Concentrating solar power systems can be sized for village power (10 kilowatts) or grid-connected applications (up to 100 megawatts). Some systems use thermal storage during cloudy periods or at night. Others can be combined with natural gas such that the resulting hybrid power plants can provide higher-value, dispatchable power.

- To-date, the primary use of CSP systems has been for bulk power supply to the southwestern grid. However, these systems were installed under very attractive power purchase rates that are not generally available today. With one of the best direct normal insolation resources anywhere on Earth, the southwestern states are still positioned to reap large and, as yet, largely uncaptured economic benefits from this important natural resource. California, Nevada, Arizona, and New Mexico are each exploring policies that will nurture the development of their solar-based industries.

- In addition to the concentrating solar power projects under way in this country, a number of projects are being developed in India, Egypt, Morocco, and Mexico. In addition, independent power producers are in the early stages of design and development for potential parabolic trough and/or power tower projects in Greece (Crete) and Spain. Given successful deployment of systems in one or more of these initial markets, several domestic project opportunities are expected to follow.
- Distributed systems deployment opportunities are emerging for dish-engine systems. Many states are adopting green power requirements in the form of "portfolio standards" and renewable energy mandates. While the potential markets in the U.S. are large, the size of developing worldwide markets is immense. The International Energy Agency projects an increased demand for electrical power worldwide more than doubling installed capacity. More than half of this is in developing countries and a large part is in areas with good solar resources, limited fossil fuel supplies, and no power distribution network. The potential payoff for dish/engine system developers is the opening of these immense global markets for the export of power generation systems.

Current Status

- CSP technology is generally still too expensive to compete in widespread domestic markets without significant subsidies. Consequently, RD&D goals are to reduce costs of CSP systems to 5 to 8¢/kWh with moderate production levels within five years, and below 5c/kWh at high production levels in the long term.
- Nine parabolic trough plants, with a total rated capacity of 354 MWe, were installed in California between 1985 and 1991. Their continuing operation has demonstrated their ability to achieve commercial costs of about 12 to 14¢/kWh.
- Solar Two, a 10-MWe pilot power tower with three hours of storage, also installed in California, provided technical information needed to scale up to a 30-100 MW commercial plant, the first of which is now being planned in Spain.
- A number of prototype dish/Stirling systems are currently operating in Nevada, Arizona, Colorado, and Spain. High levels of performance have been established; durability remains to be proven, although some systems have operated for more than 10,000 hours.
- The CSP industry includes 25 companies who design, sell, own, and/or operate energy systems and power plants based on the concentration of solar energy. CSP companies include energy utilities, independent power producers or project developers, equipment manufacturers, specialized development firms, and consultants. While some firms only offer CSP products, many offer related energy products and services. Four of the 25 are "Fortune 500 Companies." Current companies include:

Duke Solar Energy, LLC
Nexant (a Bechtel Technology & Consulting Company)
The Boeing Company
KJC Operating Company
SunRay Corporation
Arizona Public Service Corporation
Spencer Management Associates
Kearney & Associates
Nagel Pump
Clever Fellows Innovative Consortium
Array Technologies
Concentrating Technologies
Ed Tek Inc.
Stirling Energy Systems
Science Applications International Corp.
STM Corporation
WGAssociates
Morse & Associates
United Innovations Inc.
Reflective Energies
Industrial Solar Technologies
Spectralab
Salt River Project
Energy Laboratories Inc.
Amonix

Technology History

Organized, large-scale development of solar collectors began in the United States in the mid-1970s under the Energy Research and Development Administration (ERDA) and continued with the establishment of the U.S. Department of Energy (DOE) in 1978.

Troughs:

- Parabolic trough collectors capable of generating temperatures greater than 500ºC (932 F) were initially developed for industrial process heat (IPH) applications. Acurex, SunTec, and Solar Kinetics were the key parabolic trough manufacturers in the United States during this period.
- Parabolic trough development also was taking place in Europe and culminated with the construction of the IEA Small Solar Power Systems (SSPS) Project/Distributed Collector System in Tabernas, Spain, in 1981. This facility consisted of two parabolic trough solar fields – one using a single-axis tracking Acurex collector and one the double-axis tracking parabolic trough collectors developed by M.A.N. of Munich, Germany.
- In 1982, Luz International Limited (Luz) developed a parabolic trough collector for IPH applications that was based largely on the experience that had been gained by DOE/Sandia and the SSPS projects.
- Southern California Edison (SCE) signed a power purchase agreement with Luz for the Solar Electric Generating System (SEGS) I and II plants, which came online in 1985. Luz later signed a number of Standard Offer (SO) power purchase contracts under the Public Utility Regulatory Policies Act (PURPA), leading to the development of the SEGS III through SEGS IX projects. Initially, the plants were limited by PURPA to 30 MW in size; later this limit was raised to 80 MW. In 1991, Luz filed for bankruptcy when it was unable to secure construction financing for its 10th plant (SEGS X).
- The 354 MWe of SEGS trough systems are still being operated today. Experience gained through their operation will allow the next generation of trough technology to be installed and operated much more cost-effectively.

Power Towers:

- A number of experimental power tower systems and components have been field-tested around the world in the past 15 years, demonstrating the engineering feasibility and economic potential of the technology.
- Since the early 1980s, power towers have been fielded in Russia, Italy, Spain, Japan, and the United States.
- In early power towers, the thermal energy collected at the receiver was used to generate steam directly to drive a turbine generator.
- The U.S.-sponsored Solar Two was designed to demonstrate the dispatchability provided by molten-salt storage and to provide the experience necessary to lessen the perception of risk from these large systems.
- U.S. Industry is currently pursuing a subsidized power tower project opportunity in Spain. This project, dubbed “Solar Tres,” represents a 4x scale-up of the Solar 2 design.

Dish/Engine Systems:

- Dish/engine technology is the oldest of the solar technologies, dating back to the 1800s when a number of companies demonstrated solar-powered steam-Rankine and Stirling-based systems.
- Development of modern technology began in the late 1970s and early 1980s. This technology used directly illuminated, tubular solar receivers, a kinematic Stirling engine developed for automotive applications, and silver/glass mirror dishes. Systems, nominally rated at 25 kWe, achieved solar-to-electric conversion efficiencies of around 30% (still the world record to date). Eight prototype systems were deployed and operated on a daily basis from 1986 through 1988.
- In the early 1990s, Cummins Engine Company attempted to commercialize dish/Stirling systems

based on free-piston Stirling engine technology. Efforts included a 5 to 10 kWe dish/Stirling system for remote power applications, and a 25 kWe dish/engine system for utility applications. However, largely because of a corporate decision to focus on its core diesel-engine business, Cummins canceled their solar development in 1996. Technical difficulties with Cummins' free-piston Stirling engines were never resolved.

- Current dish/engine efforts are being continued by three U.S. industry teams - Science Applications International Corp. (SAIC) teamed with STM Corp., Boeing with Stirling Energy Systems, and WG Associates with Sunfire Corporation. SAIC and Boeing together have five 25kW systems under test and evaluation at utility, industry, and university sites in Arizona, California, and Nevada. WGA has two 10kW systems under test in New Mexico, with a third off-grid system being developed in 2002 on an Indian reservation for water-pumping applications.

Technology Future

The levelized cost of electricity (in constant 1997$/kWh) for the three CSP configurations are projected to be:

	2000	2010	2020
Trough	9.5	5.4	4.4
Power Tower	9.5	4.8	3.6
Dish/Engine	17.9	6.1	5.5

Source: *Renewable Energy Technology Characterizations*, EPRI TR-109496 for Dish/Engine, and Program values for Trough and Power Tower.

- RD&D efforts are targeted to improve performance and lifetime, reduce manufacturing costs with improved designs, provide advanced designs for long-term competitiveness, and address barriers to market entry.
- Improved manufacturing technologies are needed to reduce the cost of key components, especially for first-plant applications where economies of scale are not yet available.
- Demonstration of Stirling engine performance and reliability in the field are critical to the success of dish/engine systems.
- DOE expects Dish/Stirling systems to be available by 2005, after deployment and testing of 1 MW (40 systems) during the next two years.
- Key DOE program activities are targeted to support the next commercial opportunities for these technologies, demonstrate improved performance and reliability of components and systems, reduce energy costs, and develop advanced systems and applications.
- The successful conclusion of Solar Two sparked worldwide interest in power towers. As Solar Two completed operations, an international consortium led by U. S. industry including Bechtel and Boeing (with technical support from Sandia National Laboratories), formed to pursue power tower plants worldwide, especially in Spain (where special solar premiums make the technology cost-effective), but also in Egypt, Morocco, and Italy. Their first commercial power tower plant is planned to be four times the size of Solar Two (about 40 MW equivalent, utilizing storage to power a 15MW turbine up to 24 hours per day).
- The World Bank’s Solar Initiative is pursuing CSP technologies for less-developed countries. The World Bank considers CSP as a primary candidate for Global Environment Facility funding, which could total $1B to $2B for projects over the next 2 years.

Concentrating Solar Power

Market Data

U.S. Installations (electric only)

Source: *Renewable Energy Project Information System (REPiS), Version 5, NREL, 2001, and Renewable Energy Technology Characterizations, EPRI TR-109496.*

Cumulative (MW)	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
U.S.	0	24	274	354	364	364	364	364	354
Power Tower	0	10	0	0	10	10	10	10	0
Trough	0	14	274	354	354	354	354	354	354
Dish/Engine	0	0	0	0	0	0	0.125	0.125	0.125

Annual Generation from Cumulative Installed Capacity (Billion kWh)

Source: EIA, AEO 1998-2002- Table A17, Renewable Resources in the Electric Supply, 1993- Table 4, and Monthly Energy Review, December 2001- Table 7.2.

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
U.S.			0.63	0.82	0.90	0.89	0.89	0.87	0.87

Technology Performance

Efficiency

Source: *Renewable Energy Technology Characterizations, EPRI TR-109496, 1997 (this document is currently being updated by NREL and the values most likely will change), and TC revisions made by Hank Price of NREL for Trough technologies and Scott Jones of Sandia National Laboratory for Power Towers in 2001.*

		1980	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
Capacity Factor (%)	Power Tower			20.0	43.0	44.0	65.0	71.0	77.0
	Trough			34.0	33.3	41.7	51.2	51.2	51.2
	Dish			12.4	50.0	50.0	50.0	50.0	50.0
Solar to Electric Eff. (%)	Power Tower			8.5	15.0	16.2	17.0	18.5	20.0
	Trough			10.7	13.1	13.9	14.8	14.8	15.6
	Dish/Engine								

Cost*		1980	1990	1995	2000	2005	2010	2015	2020
Total ($/kWp)	Power Tower				1,747	1,294	965	918	871
	Trough			4,033	2,103	1,633	1,277	1,185	1,072
	Dish/Engine			12,576	5,191	2,831	1,365	1,281	1,197
Total ($/kWnameplate)	Power Tower				3,145	2,329	2,605	2,475	2,345
	Trough			4,033	3,154	2,988	2,766	2,568	2,323
	Dish/Engine			12,576	5,691	3,231	1,690	1,579	1,467
O&M ($/kWh)	Power Tower			0.171	0.018	0.006	0.005	0.004	0.004
	Trough			0.025	0.017	0.013	0.009	0.007	0.007
	Dish/Engine			0.210	0.037	0.023	0.011	0.011	0.011
Levelized Cost of Energy	Power Tower				0.101	0.066	0.051	0.044	0.038
($/kWh)	Trough			0.160	0.101	0.077	0.057	0.052	0.047
	Dish/Engine				0.179		0.061	0.058	0.055

* Cost data for Trough and Power Tower technologies are from 2001 revisions (in 2001$). Dish/Engine data for $/kWp excludes costs of hybrid system and $/kWnameplate includes hybrid costs (in 1997$).

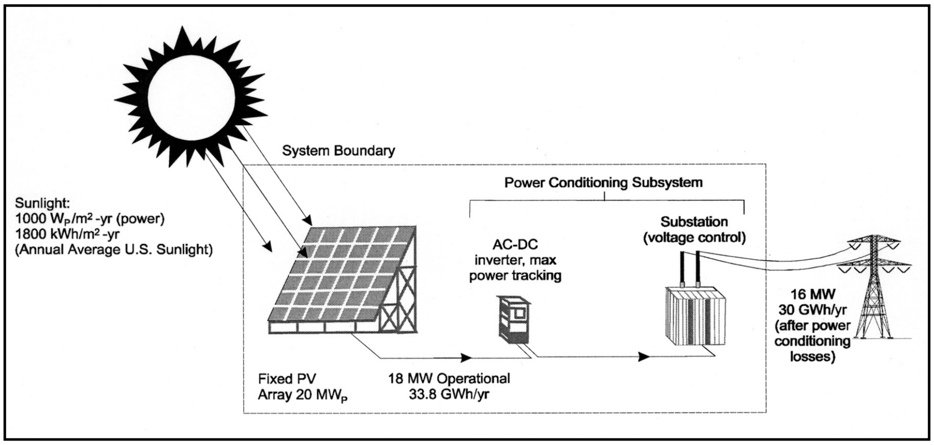
Photovoltaics

Technology Description

Photovoltaic (PV) arrays convert sunlight to electricity without moving parts and without producing fuel wastes, air pollution, or greenhouse gases (GHGs). Using solar PV for electricity and eventually transportation (from hydrogen production) will help reduce CO_2 worldwide.

System Concepts

- Flat-plate PV arrays use global sunlight; concentrators use direct sunlight. Modules are mounted on a stationary array or on single- or dual-axis sun trackers. Arrays can be ground-mounted or on all types of buildings and structures (e.g., see semi-transparent solar canopy, right). PV dc output can be conditioned into grid-quality ac electricity, or dc can be used to charge batteries or to split water to produce H_2.



Representative Technologies

- Flat-plate cells are either constructed from crystalline silicon cells, or from thin films using amorphous silicon. Other materials such as copper indium diselinide (CIS) and cadmium telluride also hold promise as thin-film materials. The vast majority of systems installed today are in flat- plate configurations where multiple cells are mounted together to form a module. These systems are generally fixed in a single position, but can be mounted on structures that tilt toward the sun on a seasonal basis, or on structures that roll east to west over the course of the day.
- Photovoltaic concentrator systems use optical concentrators to focus direct sunlight onto solar cells for conversion to electricity. A complete concentrating system includes concentrator modules, support and tracking structures, a power-processing center, and land. PV concentrator module components include solar cells, an electrically isolating and thermally conducting housing for mounting and interconnecting the cells, and optical concentrators. The solar cells in today's concentrators are predominantly silicon, although gallium arsenide-based (GaAs) solar cells may be used in the future because of their high-conversion efficiencies. The housing places the solar cells at the focus of the optical concentrator elements and provides means for dissipating excess heat generated in the solar cells. The optical concentrators are generally Fresnel lenses but also can be reflectors.

Technology Applications

- PV systems can be installed as either grid supply technologies or as customer-sited alternatives to retail electricity. As suppliers of bulk grid power, PV modules would typically be installed in large array fields ranging in total peak output from a few megawatts on up. Very few of these systems have been installed to-date. A greater focus of the recent marketplace is on customer-sited systems, which may be installed to meet a variety of customer needs. These installations may be residential-size systems of just one kilowatt or commercial-size systems of several hundred kilowatts. In either case, PV systems meet customer needs for alternatives to purchased power, reliable power, protection from price escalation, desire for green power, etc. Interest is growing in the use of PV systems as part of the building structure or façade (“building integrated”). Such systems use PV modules designed to look like shingles, windows, or other common building elements.

- PV systems are expected to be used in the United States for residential and commercial buildings; distributed utility systems for grid support; peak power shaving, and intermediate daytime load following; with electric storage and improved transmission, for dispatchable electricity; and H_2 production for portable fuel.
- Other applications for PV systems include electricity for remote locations, especially for billions of people worldwide who do not have electricity. Typically, these applications will be in hybrid mini-grid or battery-charging configurations.
- Almost all locations in the United States and worldwide have enough sunlight for PV (e.g., U.S. sunlight varies by only about 25% from an average in Kansas).
- Land area is not a problem for PV. Not only can PV be more easily sited in a distributed fashion than almost all alternatives (e.g., on roofs or above parking lots), a PV-generating station 140 km by 140 km sited at an average solar location in the United States could generate all of the electricity needed in the country (2.5×10^6 GWh/year), assuming a system efficiency of 10% and an area packing factor of 50% (to avoid self-shading). This area (0.3% of U.S.) is less than one-third of the area used for military purposes in the United States.

Current Status

- The cost of PV-generated electricity has dropped 15- to 20-fold; and grid-connected PV systems currently sell for about \$5–\$10/W_p (20 to 50¢/kWh), including support structures, power conditioning, and land. They are highly reliable and last 20 years or longer.
- Crystalline silicon is widely used and the most commercially mature photovoltaic material. Thin-film PV modules currently in production include three based on amorphous silicon, cadmium telluride and CIS alloys.
- About 288 MW of PV were sold in 2000 (more than \$2 billion worth); total installed PV is more than 1 GW. The U.S. world market share is about 26%. Annual market growth for PV has been about 25% as a result of reduced prices and successful global marketing. In recent years, sales growth has accelerated to almost 40% per year. Hundreds of applications are cost-effective for off-grid needs. Almost two-thirds of U.S.-manufactured PV is exported. However, the fastest growing segment of the market is grid-connected PV, such as roof-mounted arrays on homes and commercial buildings in the United States. CA is subsidizing PV systems because it is considered cost-effective to reduce their dependence on natural gas, especially for peak daytime loads for air-conditioning, which matches PV output.
- Highest efficiency for wafers of single-crystal or polycrystalline silicon is 24%, and for commercial modules is 13%–15%. Silicon modules currently cost about \$2-\$3/W_p to manufacture.
- During the past 2 years, *world record* solar cell sunlight-to-electricity conversion efficiencies were set by federally funded universities, national laboratories, or industry in copper indium gallium diselenide (19% cells and 12% modules) and cadmium telluride (16% cells, 11% modules). Cell and module efficiencies for these technologies have increased more than 50% in the past decade. Efficiencies for commercial thin-film modules are 5%–11%. A new generation of thin-film PV modules is going through the high-risk transition to first-time and large-scale manufacturing. If successful, market share could increase rapidly.
- Highest efficiencies for single-crystal Si and multijunction gallium arsenide (GaAs)-alloy cells for concentrators are 25%–34%; and for commercial modules are 15%–17%. Prototype systems are being tested in the U.S. desert SW.
- Current leading PV companies in 2000 and associated production of cells/modules are listed below:

	U.S. Production (2000)	World Production
	MW	MW
BP/Amoco Solarex	22.0	41.0
Kyocera	-	42.0
Sharp	-	50.4
Siemens	28	28.0
Astropower	18.0	18.0
Sanyo	-	17.0
Photowatt	-	14.0
ASE (GMBH)	-	12.0
Solec Intl	-	-
Advanced PV Sys.	-	-
USSC	3.0	-
ASE Americas	6.0	-
Others	1.5	-
Total (for leading producers)	78.5	222.4

Source: PV News, Vo. 20, No. 2, Page 2

Technology History

- French physicist Edmond Becquerel first described the photovoltaic (PV) effect in 1839, but it remained a curiosity of science for the next three quarters of a century. At only 19, Becquerel found that certain materials would produce small amounts of electric current when exposed to light. The effect was first studied in solids, such as selenium, by Heinrich Hertz in the 1870s. Soon afterward, selenium PV cells were converting light to electricity at 1 percent to percent efficiency. As a result, selenium was quickly adopted in the emerging field of photography for use in light-measuring devices.
- Major steps toward commercializing PV were taken in the 1940s and early 1950s, when the Czochralski process was developed for producing highly pure crystalline silicon. In 1954, scientists at Bell Laboratories depended on the Czochralski process to develop the first crystalline silicon photovoltaic cell, which had an efficiency of 4 percent. Although a few attempts were made in the 1950s to use silicon cells in commercial products, it was the new space program that gave the technology its first major application. In 1958, the U.S. Vanguard space satellite carried a small array of PV cells to power its radio. The cells worked so well that PV technology has been part of the space program ever since.
- Even today, PV plays an important role in space, supplying nearly all power for satellites. The commercial integrated circuit technology also contributed to the development of PV cells. Transistors and PV cells are made from similar materials and operate on similar physical mechanisms. As a result, advances in transistor research provided a steady flow of new information about PV cell technology. (Today, however, this technology transfer process often works in reverse, as advances in PV research and development are sometimes adopted by the integrated circuit industry.)
- Despite these advances, PV devices in 1970 were still too expensive for most "down to Earth" uses. But, in the mid-1970s, rising energy costs, sparked by a world oil crisis, renewed interest in making PV technology more affordable. Since then, the federal government, industry, and research organizations have invested billions of dollars in research, development, and production. A thriving industry now exists to meet the rapidly growing demand for photovoltaic products.

Technology Future

The levelized cost of electricity (in constant 1997$/kWh) for PV are projected to be:

	2000	2010	2020
Utility-owned Residential (crystalline Si)	29.7	17.0	10.2
Utility Scale Thin Film	29.0	8.1	6.2
Concentrator	24.4	9.4	6.5

Source: *Renewable Energy Technology Characterizations*, EPRI TR-109496.
(Note that this document is currently being updated by DOE and the values most likely will change).

- Crystalline Silicon - Most PV systems installed to-date have used crystalline silicon cells. That technology is relatively mature. In the future, cost-effectiveness will be achieved through incremental efficiency improvements, enhanced yields, and advanced lower-cost manufacturing techniques.
- Even though some thin-film modules are now commercially available, their real commercial impact is only expected to become significant during the next three to 10 years. Beyond that, their general use should occur in the 2005-2015 time frame, depending on investment levels for technology development and manufacture.
- Thin films using amorphous silicon, which are a growing segment of the U.S. market, have several advantages over crystalline silicon. It can be manufactured at lower cost, is more responsive to indoor light, and can be manufactured on flexible or low-cost substrates. Improved semiconductor deposition rates will reduce manufacturing costs in the future. Other thin-film materials will become increasingly important in the future. In fact, the first commercial modules using indium gallium diselinide thin-film devices were produced in 2000. Improved manufacturing techniques and deposition processes will reduce costs and help improve efficiency.
- Substantial commercial interest exists in scaling-up production of thin films. As thin films are produced in larger quantity, and as they achieve expected performance gains, they will become more economical for the whole range of applications.
- Multijunction cells with efficiencies of 38% at very high concentrations are being developed.
- Manufacturing research and supporting technology development hold important keys to future cost reductions. Large-scale manufacturing processes will allow major cost reductions in cells and modules. Advanced power electronics and non-islanding inverters will lessen barriers to customer adoption and utility interface.
- A unique multijunction GaAs-alloy cell developed at NREL was spun off to the space power industry, leading to a record cell (34%) and a shared R&D100 Award for NREL/Spectrolab in 2001. This device configuration is expected to dominate future space power for commercial and military satellites.

Photovoltaics

Market Data

PV Cell/Module Production (Shipments) Source: *PV News, Vol. 15, No. 2, Feb. 1996, Vol. 16, No. 2, Feb. 1997, & Vol. 20, No. 2, Feb. 2001, and [Paul Maycock, www.pvenergy.com]*

Annual (MW)	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
U.S.	3	8	15	35	39	51	54	61	75	105
Japan	1	10	17	16	21	35	49	80	129	171
Europe	0	3	10	20	19	30	34	40	61	88
Rest of World	0	1	5	6	10	9	19	21	23	32
World Total	4	23	47	78	89	126	155	201	288	396
Cumulative (MW)	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
U.S.	5	45	101	219	258	309	363	424	498	604
Japan	1	26	95	185	206	241	290	370	498	670
Europe	1	13	47	136	155	185	219	259	319	408
Rest of World	0	3	20	45	55	65	83	104	127	159
World Total	7	87	263	585	674	800	954	1,156	1,443	1,839
US % of World Sales	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
Annual	71%	34%	32%	44%	44%	41%	35%	30%	26%	27%
Cumulative	75%	52%	39%	37%	38%	39%	38%	37%	35%	33%

Annual Capacity (Shipments retained, MW)* Source: *Strategies Unlimited*

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
U.S.	1.4	4.2	5.1	8.4	9.2	10.5	13.6	18.4	21.3
Total World	3	15	39	68	79	110	131	170	246

*Excludes indoor consumer (watches/calculators).

Cumulative Capacity (Shipments retained, MW)* Source: *Strategies Unlimited*	1980	1985	1990	1995	1996	1997	1998	1999	2000
U.S.	3	23	43	76	85	96	109	128	149
Total World	6	61	199	474	552	663	794	964	1,210

*Excludes indoor consumer (watches/calculators).

U.S. Shipments (MW) — Source: *Energy Information Administration, Annual Energy Review, 2000, Tables 10.5 and 10.6, and REA 2000, Table 24.*

Annual Shipments	1980	1985	1990	1995	1996	1997	1998	1999	2000
Total		5.8	13.8	31.1	35.5	46.4	50.6	76.8	88.2
Imports		0.3	1.4	1.3	1.9	1.9	1.9	4.8	
Exports	N/A	1.7	7.5	19.9	22.4	33.8	35.5	55.6	58.4
Domestic Total On-Grid*		0.4	0.2	1.7	1.8	2.2	4.2	6.9	7.3
Domestic Total Off-Grid*		3.7	6.1	9.5	11.2	10.3	10.8	14.4	22.5
Cumulative Shipments	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Total		35.2	84.7	193.3	228.8	275.2	325.7	402.5	490.7
Imports		1.0	5.6	14.3	16.2	18.0	19.9	24.7	
Exports	N/A	5.7	32.9	104.0	126.5	160.3	195.8	251.3	309.7
Domestic Total On-Grid*		2.9	4.7	8.2	9.9	12.2	16.4	23.3	30.6
Domestic Total Off-Grid*		26.6	47.2	81.1	92.4	102.7	113.5	127.9	150.4

* Domestic Totals include imports and exclude exports.

Annual U.S. Installations (MW) — Source: *The 2000 National Survey Report of Photovoltaic Power Applications in the United States, prepared by Paul D. Maycock and Ward Bower, April 30, 2001, prepared for the IEA, Table E-1.*

	1980	1985	1990	1995	1996	1997	1998	1999	2000
Grid-Connected Distributed				1.5	2.0	2.0	2.2	3.7	5.5
Off-Grid Consumer				3.5	4.0	4.2	4.5	5.5	6.0
Government				0.8	1.2	1.5	1.5	2.5	2.5
Off-Grid Industrial/Commercial	N/A	N/A	N/A	4.0	4.4	4.8	5.2	6.5	7.5
Consumer (<20 w)				2.0	2.2	2.2	2.4	2.5	2.5
Central Station				0.0	0.0	0.0	0.0	0.0	0.0
Total				11.8	13.8	14.7	15.8	20.7	24.0

Cumulative U.S. Installations* (MW)

Source: *The 2000 National Survey Report of Photovoltaic Power Applications in the United States, prepared by Paul D. Maycock and Ward Bower, April 30, 2001, prepared for the IEA, Table 1.*

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Off-grid Residential				19.3	23.3	27.5	32.0	37.5	43.5
Off-grid non-Residential				25.8	30.2	35.0	40.2	46.7	55.2
On-grid Distributed	N/A	N/A	N/A	9.7	11.0	13.7	15.9	21.1	28.1
On-grid Centralized				12.0	12.0	12.0	12.0	12.0	12.0
Total				66.8	76.5	88.2	100.1	117.3	138.8

* Excludes installations less than 40kW.

Annual World Installations (MW)

Source: *PV News, Vol. 19, No.11, Nov. 2000*

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Consumer Products			16		22	26	30	35	40
US Off-Grid Residential			3		8	9	10	13	16
World Off-Grid Rural			6		15	19	24	31	35
Communications/ Signal	N/A	N/A	14	N/A	23	28	31	35	42
PV/Diesel, Commercial			7		12	16	20	25	30
Grid-Conn Res, Commercial			1		7	27	35	60	85
Central Station (>100kW)			1		2	2	2	2	2
Total			48		89	127	152	201	250

Annual U.S. Shipments by Cell Type (MW)

Source: *PV News, Vol. 15, No. 2, Feb. 1996, Vol. 16, No. 2, Feb. 1997, Vol. 17, No. 2, Feb. 1998, Vol. 18, No. 2, Feb. 1999, Vol. 19, No. 3, March. 2000, and Vol. 20, No. 3, March 2001.*

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Single Crystal				22.0	24.1	31.8	30.0	36.6	44.0
Flat Plate Polycrystal (other than ribbon)				9.0	10.3	14.0	14.7	16.0	17.0
Amorphous Silicon				1.3	1.1	2.5	3.8	5.3	6.5
Crystal Silicon Concentrators				0.3	0.7	0.7	0.2	0.5	0.5
Ribbon Silicon	N/A	N/A	N/A	2.0	3.0	4.0	4.0	4.2	5.0
Cadmium Telluride				0.1	0.4	0.0	0.0	0.0	0.0
SI on Low-Cost-Sub				0.1	0.3	0.5	1.0	2.0	2.0
A-SI on Cz Slice									0.0
Total				34.8	39.9	53.5	53.7	64.6	75.0

Annual World Shipments by Cell Type (MW)

Source: *PV News, Vol. 15, No. 2, Feb. 1996, Vol. 16, No. 2, Feb. 1997, Vol. 17, No. 2, Feb. 1998, Vol. 18, No. 2, Feb. 1999, Vol. 19, No. 3, March. 2000, and Vol. 20, No. 3, March 2001.*

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Single Crystal				46.7	48.5	62.8	59.8	73.0	89.7
Flat Plate Polycrystal				20.1	24.0	43.0	66.3	88.4	140.6
Amorphous Silicon				9.1	11.7	15.0	19.2	23.9	27.0
Crystal Silicon Concentrators				0.3	0.7	0.2	0.2	0.5	0.5
Ribbon Silicon	N/A	N/A	N/A	2.0	3.0	4.0	4.0	4.2	14.7
Cadmium Telluride				1.3	1.6	1.2	1.2	1.2	1.2
SI on Low-Cost-Sub				0.1	0.3	0.5	1.0	2.0	2.0
A-SI on Cz Slice								8.1	12.0
Total				79.5	89.8	126.7	151.7	201.3	287.7

Annual U.S. Shipments by Cell Type (MW)

Source: EIA, *Renewable Energy Annual 1997, Table 27, Renewable Energy Annual 2000, Table 26, and Solar Collector Manufacturing Activity annual reports, 1982-1992.*

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Single-Crystal Silicon				19.9	21.7	30.0	30.8	47.2	
Cast and Ribbon Crystalline Silicon				9.9	12.3	14.3	16.4	26.2	
Crystalline Silicon Total		5.5	12.5	29.8	34.0	44.3	47.2	73.5	
Thin-Film Silicon	N/A	0.3	1.3	1.3	1.4	1.9	3.3	3.3	N/A
Concentrator Silicon				0.1	0.2	0.2	0.1	0.1	
Other									
Total		5.8	13.8	31.2	35.6	46.3	50.6	76.8	

Annual Grid Connected Capacity (MW)

Source: *The 2000 National Survey Report of Photovoltaic Power Applications in the United States, prepared by Paul D. Maycock and Ward Bower, April 30, 2001, for the IEA, derived from Table 1; Japan data from PV News, Vol. 20, No. 7, July 2001.*

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
U.S.	N/A	N/A	N/A		1.3	2.7	2.2	5.2	7.0
Japan				3.9	7.5	19.5	24.1	57.7	95.8

Cumulative Grid Connected Capacity (MW)

Source: *The 2000 National Survey Report of Photovoltaic Power Applications in the United States, prepared by Paul D. Maycock and Ward Bower, April 30, 2001, for the IEA, Table 1; Japan data from PV News, Vol. 20, No. 7, July 2001.*

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
U.S.	N/A	N/A	N/A	21.7	23.0	25.7	27.9	33.1	40.1
Japan				5.80	13.3	32.8	56.9	115	210

Annual US Installed Capacity (MW)

Source: *Renewable Electric Plant Information System (REPiS), Version 5, NREL, 2001.*

Top Ten States	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
California		0.034	0.016	0.720	0.900	0.606	0.577	2.993	3.412
Arizona		0.004		0.026	0.067	0.732	0.296	0.578	0.540
New York			0.013	0.067	0.344	0.021	0.346	0.041	0.377
Texas	0.006	0.015	0.002	0.015		0.010	0.112	0.144	0.120
Colorado				0.018	0.100	0.056	0.132	0.344	0.137
Hawaii				0.013	0.031	0.008	0.291	0.113	0.459
Georgia					0.352			0.019	0.221
Florida	0.009		0.008	0.018		0.036	0.054	0.107	0.172
Massachusetts		0.006		0.018		0.023	0.075	0.037	0.020
Washington, D.C.								0.009	0.003
Total U.S.	0.020	0.080	0.050	1.050	2.035	1.678	1.979	5.040	6.076

Cumulative U.S. Installed Capacity (MW)

Source: *Renewable Electric Plant Information System (REPiS), Version 5, NREL, 2001.*

Top Ten States	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
California	0.002	1.369	2.803	6.495	7.396	8.002	8.579	11.572	14.983
Arizona	0.008	0.032	0.048	0.097	0.164	0.896	1.192	1.771	2.311
New York	0.000	0.000	0.013	0.226	0.569	0.590	0.936	0.977	1.353
Texas	0.006	0.021	0.296	0.374	0.374	0.384	0.496	0.640	0.760
Colorado	0.000	0.000	0.010	0.040	0.140	0.146	0.278	0.622	0.759
Hawaii	0.000	0.014	0.033	0.046	0.077	0.085	0.376	0.489	0.735
Georgia	0.000	0.000	0.000	0.000	0.352	0.352	0.352	0.371	0.592
Florida	0.009	0.093	0.117	0.135	0.135	0.171	0.225	0.332	0.504
Massachusetts	0.000	0.127	0.208	0.238	0.238	0.261	0.336	0.373	0.393
Washington, D.C.	0.000	0.337	0.337	0.349	0.349	0.349	0.349	0.358	0.361
Total U.S.	0.025	2.104	4.099	8.511	10.546	12.224	14.204	19.244	25.319

Technology Performance

Source: *Renewable Energy Technology Characterizations, EPRI TR-109496, 1997.C185*
(This document is currently being updated by DOE and the values most likely will change).

Efficiency		**1980**	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
Cell (%)	Crystalline Silicon			24	24.7				
	Thin Film			18.0	19.0	20.0	21.0	21.5	22.0
	Concentrator			20.0	23.0	26.0	33.0	35.0	37.0
Module (%)	Crystalline Silicon			14.0	16.0	17.0	18.0	18.5	19.0
	Thin Film	N/A	N/A	10.0	12.0	15.0	17.0	17.5	18.0
	Concentrator								
System (%)	Crystalline Silicon			11.3	13.1	14.1	15.1	15.6	16.1
	Thin Film			4.8	7.2	8.8	11.2	12.0	12.8
	Concentrator			13.8	15.1	17.1	21.7	23.0	24.3

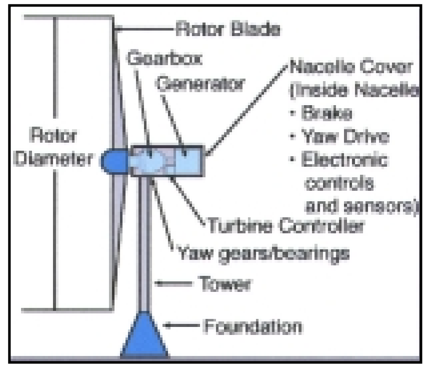
Cost		**1980**	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
Module ($/Wp)	Crystalline Silicon			3.8	3.0	2.3	1.8	1.4	1.1
	Thin Film			3.8	2.2	1.0	0.5	0.4	0.4
	Concentrator			1.8	1.5	0.7	0.6	0.5	0.5
BOS ($/Wp)	Crystalline Silicon			2.7	2.1	1.6	1.2	0.9	0.7
	Thin Film			3.7	2.1	1.3	0.7	0.6	0.5
	Concentrator	N/A	N/A	3.6	2.7	1.2	1.0	0.8	0.7
Total ($/Wp)	Crystalline Silicon *			6.5	5.1	3.9	3.0	2.4	1.8
	Thin Film			7.5	4.3	2.3	1.2	1.1	0.9
	Concentrator			7.6	4.0	2.0	1.6	1.3	1.1
O&M ($/kWh)	Crystalline Silicon			0.008	0.007	0.006	0.006	0.006	0.005
	Thin Film			0.023	0.008	0.003	0.002	0.002	0.001
	Concentrator			0.047	0.020	0.010	0.008	0.007	0.006

***** Range in total capital cost for Crystalline Silicon in 2000 is $5.1/Wp to $9.1/Wp depending on market supply and demand. (Source: John Mortensen, Factors Associated with Photovoltaic System Costs, June 2001, NREL/TP 620.29649, Page 3).

Wind Energy

Technology Description

Wind turbine technology converts the kinetic energy in the wind to mechanical energy and ultimately to electricity. Grid-connected wind power reduces GHG emissions by displacing the need for natural gas- and coal-fired generation. Village and off-grid applications are important for displacing diesel generation and for improving quality of life, especially overseas.



System Concepts

- The principle of wind energy conversion is simple: Wind passing over the blade creates lift, producing a torque on the rotor shaft that turns a gearbox. The gearbox is coupled to an electric generator that produces power at the frequency of the host power system. Some new innovative designs use low-speed generators, which eliminate the need for a gearbox.

Representative Technologies

- Two major design approaches are being used: (1) typical of historic European technology—3-bladed, up-wind, stiff, heavy machines that resist cyclic and extreme loads, and (2) lightweight, flexible machines that bend and absorb loads, primarily being developed by U.S. designers. Several alternative configurations within each approach are being pursued.

Technology Applications

- Thirty-seven states have land area with good winds (13 mph annual average at 10 m height, wind class 4, or better).
- For wind-farm or wholesale power applications, the principal competition is natural gas for new construction and natural gas in existing units for fuel saving. Utility restructuring is a critical challenge to increased deployment in the near-term because it emphasizes short-term, low-capital-cost alternatives and lacks public policy to support deployment of sustainable technologies such as wind energy.

Current Status

- Wind technology is competitive today in bulk power markets with support from the production tax credit, and in high-value niche applications or markets that recognize noncost attributes.
- Current performance is characterized by levelized costs of 4 to 5.5¢/kWh (depending on resource intensity and financing structure), capacity factors of 30 to 40 percent, availability of 95 to 98%, total installed project costs ("overnight" – not including construction financing) of $800 to $1,100/kW, and efficiencies of 65 to 75% of the theoretical (Betz limit) maximum.
- The worldwide annual market growth rate for wind technology is at a level of 30% with new markets opening in many developing countries. Domestic public interest in environmentally responsible electric generation technology is reflected by new state energy policies and in the success of "green marketing" of wind power across the country.
- Preliminary estimates are that installed capacity at the end of 2001 was 4,260 MW in the United States, and 23,300 MW worldwide; compared to 2,550 MW in the United States and 17,653 worldwide in 2000; and 2,450 MW in the United States and 13,598 MW worldwide in 1999.
- U.S. energy generation from wind was nearly 5 TWh out of a worldwide total of 30 TWh in 2000, up from 4.5 TWh out of an approximate total of 26 TWh in 1999.
- Twelve states had more than 20 MW of large wind turbine capacity at the end of 2001, with 15 additional states having less than 20 MW each.
- In the United States, the wind industry is thinly capitalized, except for the acquisition of Enron

Wind Corporation by General Electric Co. About six manufacturers and six to 10 developers characterize the U.S. industry.

- In Europe, there are about 12 turbine manufacturers and about 20 to 30 project developers. European manufacturers have established North American manufacturing facilities and are actively participating in the U.S. market.
- Current leading wind companies and sales volume are shown below:

	U.S. Market (2001) (Estimated)		**World Market (2000)**	
	MW	Percent	MW	Percent
Vestas (DK	652	38.6	805	17.9
GE/Enron (USA)	395	23.3	270	6.0
Bonus (DK)	278	16.4	516	11.5
Mitsubishi (JP)	221	13.1	64	1.4
NEG Micon (DK)	115	6.8	601	13.4
Nordex (DK)	2.6	-	375	8.3
Enercon (D)	-	-	617	13.7
Gamesa (SP)	-	-	623	13.9
Ecotecnia (SP)	-	-	174	3.9
Suzlon (Ind)	-	-	103	2.3
Dewind (GE)	-	-	94	2.1
MADE (SP)	-	-	85	1.9
Others			165	3.7

Sources: U.S. Market – NREL, November 2001, World Market – BTM Consult, ApS, "World Market Update 2000"

Technology History

- Prior to 1980, DOE sponsored, and NASA managed, large-scale turbine development – starting with hundred-kilowatt machines and culminating in the late 1980s with the 3.2-MW, DOE-supported Mod-5 machine built by Boeing.
- Small-scale (2-20 kW) turbine development efforts also were supported by DOE at the Rocky Flats test site. Numerous designs were available commercially for residential and farm uses.
- In 1981, first wind farms were installed in California by a small group of entrepreneurial companies. PURPA provide substantial regulatory support for this initial surge.
- During the next five years, the market boomed, installing U.S., Danish, and Dutch turbines.
- By 1985, annual market growth had peaked at 400 MW. Following that, federal tax credits were abruptly ended, and California incentives weakened the following year.
- In 1988, European market exceeded the U.S. for the first time, spurred by ambitious national programs. A number of new companies emerged in the U.K. and Germany.
- In 1989, DOE's focus changed to supporting industry-driven research on components and systems. At the same time, many U.S. companies became proficient in operating the 1600 MW of installed Capacity in CA. They launched into value engineering and incremental increases in turbine size.
- DOE program supported value-engineering efforts and other advanced turbine development efforts.
- In 1992, Congress passed the Renewable Energy Production Tax Credit (REPI), which provided a 1.5 cent/kWh tax credit for wind-produced electricity. Coupled with several state programs and mandates, installations in the U.S. began to increase.
- In 1997, Enron purchased Zond Energy Systems, one of the value-engineered turbine manufacturers.
- In FY2001, DOE initiated a low wind speed turbine development program to broaden the U.S. cost-competitive resource base.
- In 2002, General Electric Co. purchased Enron Wind Corporation.

Technology Future

The levelized cost of electricity for wind energy technology is projected to be:

	2000	2002	2010	2020
Class 4	6.0	5.5	3.0	2.7
Class 6	4.2	4.0	2.4	2.2

Assumptions include: 30-year levelized cost, constant January 2002 dollars, generation company ownership/financial assumptions; wind plant comprised of 100 turbines; no financial incentives included.

Source: FY03 U.S. DOE Wind Program Internal Planning Documents, Summer 2001

- Wind energy's competitiveness by 2005 will be affected by policies regarding ancillary services and transmission and distribution regulations. Substantial cost reductions are expected for wind turbines designed to operate economically in low wind speed sites, which will increase the amount of economical wind resource areas by 20-fold, and will be within 100 miles of most load centers.
- Initial lower levels of wind deployment (up to 15–20% of the total U.S. electric system capacity) are not expected to introduce significant grid reliability issues. Inasmuch as the wind blows only intermittently, use of this technology at larger penetrations may require modification to system operations or ancillary services. Transmission infrastructure upgrades and expansion will be required for large penetrations of wind energy to service major load centers.
- Over the long-term, as more high wind sites become used, emphasis will shift toward installation in lower wind speed sites. Advances in technology will include various combinations of the following improvements, accomplished through continuing R&D:

*Tower*s– taller for more energy, softer to shed loads, advanced materials, and erection techniques to save cost

Rotors - Improving airfoils and plan forms to increase energy capture - for instance, a variable rotor diameter; larger rotors at the same cost or small cost increase by optimizing design and manufacturing, using lighter materials, and implementing controls to mitigate loads.

Drive Train and Generators – New designs to reduce weight and cost. Advances in power electronics and operational algorithms to optimize drive train efficiencies, especially by increasing low efficiencies in ranges of operation that are currently much lower than those in the peak range. In addition to new power electronics and operational approaches, possible advances include permanent magnet generators, and use of single-stage transmissions coupled with multiple smaller, simpler, off-the-shelf generators that can be purchased from high-volume manufacturers.

Controls – By reducing loads felt throughout the turbine, various approaches for passive and active control of turbines will enable larger, taller structures to be built for comparatively small cost increases, resulting in improvements in system cost of energy.

Design Codes – Reductions in design margins also will decrease the cost of turbines and allow for larger turbines to be built for comparatively small increases in cost, resulting in improvements in system cost of energy.

Foundations – New designs to lower cost.

Utility Grid Integration – Models and tools to analyze the steady and dynamic impact, and operational characteristics of large wind farms on the electricity grid will facilitate wind power integration. Improved wind forecasting and development of various enabling technologies will increase the value of wind power.

Wind

Market Data

Grid Connected Wind Capacity		*Source: Reference IEA (data supplemented by Windpower Monthly, April 2001, and 2001 data from Windpower Monthly, January 2002).*									
Cumulative (MW)		**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
	U.S.	10	1,039	1,525	1,770	1,794	1,741	1,890	2,455	2,554	4,240
	Denmark	3	50	310	630	785	1,100	1,400	1,752	2,338	2,417
	Netherlands	0	0	49	255	305	325	364	416	447	483
	Germany	2	3	60	1,137	1,576	2,082	2,874	4,445	6,095	8,100
	Spain	0	0	9	126	216	421	834	1,539	2,334	3,175
	UK	0	0	6	193	264	324	331	344	391	477
	Europe	5	58	450	2,494	3,384	4,644	6,420	9,399	12,961	16,362
	India	0	0	20	550	820	933	968	1,095	1,220	1,426
	Japan	0	0	1	10	14	7	32	75	121	250
	Rest of World	0	0	6	63	106	254	315	574	797	992
	World Total	15	1,097	2,002	4,887	6,118	7,579	9,625	13,598	17,653	23,270
		Source: Renewable Energy Project Information System (REPiS), Version 5, NREL, 2001.									
Annual (MW)		**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
	U.S.	0.0	336.6	153.7	42.7	1.4	7.6	186.1	657.7		
Cumulative (MW)											
	U.S.	0.1	674	1,569	1,778	1,779	1,787	1,973	2,631		

Annual Market Shares

Source: US DOE- 1982-87 wind turbine shipment database; 1988-94 DOE Wind Program Data Sheets; 1996-2000 American Wind Energy Association
Association

	1980	1985	1990	1995	1996	1997	1998	1999	2000
US Mfg Share of US Market	98%	44%	36%	67%	NA	38%	78%	44%	0%
US Mfg Share of World Market	65%	42%	20%	5%	2%	4%	13%	9%	6%

State Installed Capacity

Source: *American Wind Energy Association.*

Annual State Installed Capacity (MW)

Top Ten States	1980	1985	1990	1995	1996	1997	1998	1999	2000	2001
California*		N/A	N/A	3.0	0.0	8.4	0.7	250.0	0.0	67.1
Texas		0.0	0.0	41.0	0.0	0.0	0.0	139.2	0.0	915.2
Iowa		0.0	0.0	0.1	0.0	1.2	3.1	237.5	0.0	81.8
Minnesota		0.0	0.0	0.0	0.0	0.2	109.2	137.6	17.8	28.6
Washington		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	178.2
Oregon		0.0	0.0	0.0	0.0	0.0	25.1	0.0	0.0	132.4
Wyoming		0.0	0.0	0.0	0.1	0.0	1.2	71.3	18.1	50.0
Kansas		0.0	0.0	0.0	0.0	0.0	0.0	1.5	0.0	112.2
Colorado		0.0	0.0	0.0	0.0	0.0	0.0	21.6	0.0	39.6
Wisconsin		0.0	0.0	0.0	0.0	0.0	1.2	21.8	0.0	30.0
Total of 10 States		N/A	N/A	44.1	0.1	10	141	881	36	1,635
Total U.S.		N/A	N/A	44	1	16	142	884	67	1,694

Cumulative State Installed Capacity (MW)

Top Ten States (as of 2001)	1980	1985	1990	1995	1996	1997	1998	1999	2000	2001
California*		N/A	N/A	1,387	1,387	1,396	1,396	1,646	1,646	1,714
Texas		0.0	0.0	41.0	41.0	41.0	41.0	180.2	180.2	1,096
Iowa		0.0	0.0	0.7	0.8	2.0	5.0	242.5	242.5	324.2
Minnesota		0.0	0.0	25.7	25.7	25.9	135.1	272.7	290.5	319.1
Washington		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	178.2
Oregon		0.0	0.0	0.0	0.0	0.0	25.1	25.1	25.1	157.5
Wyoming		0.0	0.0	0.0	0.1	0.1	1.3	72.5	90.6	140.6
Kansas		0.0	0.0	0.0	0.0	0.0	0.0	1.5	1.5	113.7
Colorado		0.0	0.0	0.0	0.0	0.0	0.0	21.6	21.6	61.2

Wisconsin	0.0	0.0	0.0	0.0	0.0	1.2	23.0	23.0	53.0
Total of 10 States	N/A	N/A	1,455	1,455	1,465	1,605	2,486	2,521	4,157
Total U.S.	N/A	N/A	1,457	1,457	1,474	1,616	2,500	2,566	4,261

* The data set includes 1,193.53 MW of wind in California that is not given a specific installation year, but rather a range of years (1072.36 MW in 1981-1995, 87.98 in 1982-1987, and 33.19 MW in "mid-1980's"), this has led to the "Not Available" values for 1985 and 1990 for California and the totals, and this data is not listed in the annual installations, but has been added to the cumulative totals for 1995 and on.

Annual Generation from Cumulative Installed Capacity (Billion kWh)

Source: U.S. - *EIA, Monthly Energy Review, December 2001- Table 7.2.; IEA Countries - IEA Wind Energy Annual Reports, 1995-2000.*

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
U.S.			3.0	3.2	3.4	3.2	3.0	4.5	5.0
IEA Countries				7.5	8.5	11.0	12.0	22.0	26.0

Technology Performance

Energy Production

Source: *U.S.DOE Wind Program, 1980-1995, FY03 U.S.DOE Wind Program Internal Planning Documents, Summer 2001, 2000-2020*

		1980	**1985**	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
Capacity Factor (%)	Class 4		10	15	20	25.2	32.6	44.7	46.5	47.1
	Class 6		20	22	25	39.4	44.3	49.6	50.9	53.8
Specific Energy (kWh/m²*)	Class 4		500	800	850	900	1,110	1,260	1,310	1,330
	Class 6		900	1,150	1,300	1,400	1,650	1,700	1,740	1,760
Production Efficiency** (kWh/kW)	Class 4	200	650	1,300	1,750	2,200	2,860	3,500	3,600	3,600
	Class 6	800	1,700	1,900	2,200	3,450	3,880	4,350	4,450	4,700

* m^2 is the rotor swept area.

** Production Efficiency is the net energy per unit of installed capacity.

Cost*			1980	1985	1990	1995	2000	2005	2010	2015	2020
Source: *FY03 U.S. DOE Wind Program Internal Planning Documents, Summer 2001.*											
	Project Cost ($/kW)	Class 4					1,000	915	910	880	860
	(Overnight costs)	Class 6					1,000	900	800	770	750
	O&M ($/kW)	Class 4					11.0	7.9	7.0	6.9	6.6
		Class 6					17.3	8.0	7.8	7.6	7.5
	Fixed O&M & Land	Class 4					8.0	8.0	8.0	8.0	8.0
	($/kW)	Class 6					8.0	8.0	8.0	8.0	8.0

Specific Cost* (Project Capital Cost Per Rotor Captured Area - $/m2)		1980	1985	1990	1995	2000	2005	2010	2015	2020
Source: FY03 U.S. DOE Wind Program Internal Planning Documents, Summer 2001, 2000-2020.										
	Class 4					382	357	293	283	277
	Class 6					414	340	312	300	276

* Jan 2002 dollars

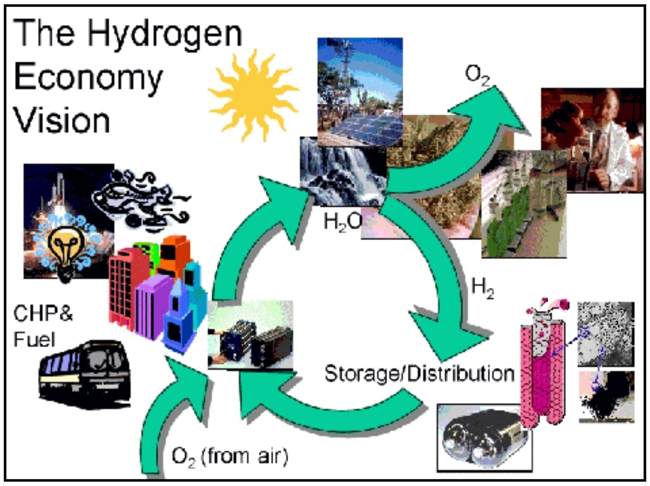
Levelized Cost of Energy* ($/kWh)		1980	1985	1990	1995	2000	2005	2010	2015	2020
Source: *U.S. DOE Wind Program 1980-1985; FY03 U.S. DOE Wind Program Internal Planning Documents, Summer 2001, 2000-2020*										
	Class 4			0.12	0.080	0.060	0.041	0.030	0.028	0.027
	Class 6			0.08	0.060	0.042	0.027	0.024	0.023	0.022

* 30-year term, constant January 2002 dollars. Generation Company Ownership/Financial Assumptions. Wind plant comprised of 100 turbines. No financial incentives are included.

Hydrogen

Technology Description

Like electricity, hydrogen can be produced from many sources, including fossil fuels, renewable resources, and nuclear energy. Hydrogen and electricity can be converted from one to the other using electrolyzers (electricity to hydrogen) and fuel cells (hydrogen to electricity). Hydrogen is an effective energy storage medium, particularly for distributed generation. When hydrogen produced from renewable resources is used in fuel cell vehicles or power devices, there are very few emissions – the major byproduct is water. With improved conventional energy conversion and carbon capture technologies, hydrogen from fossil resources can be used efficiently with few emissions.



The Hydrogen Economy vision is based on a clean and elegant cycle: separate water into hydrogen and oxygen using renewable or nuclear energy, or fossil resources with carbon sequestration. Use the hydrogen to power a fuel cell, internal combustion engine, or turbine, where hydrogen and oxygen (from air) recombine to produce electrical energy, heat, and water to complete the cycle. This process produces no particulates, no carbon dioxide, and no pollution.

System Concepts

- Hydrogen made via electrolysis from excess nuclear or renewable energy can be used as a sustainable transportation fuel or stored to meet peak-power demand. It also can be used as a feedstock in chemical processes.
- Hydrogen produced by decarbonization of fossil fuels followed by sequestration of the carbon can enable the continued, clean use of fossil fuels during the transition to a carbon-free Hydrogen Economy.
- A hydrogen system is comprised of production, storage, distribution, and use.
- A fuel cell works like a battery but does not run down or need recharging. It will produce electricity and heat as long as fuel (hydrogen) is supplied. A fuel cell consists of two electrodes—a negative electrode (or anode) and a positive electrode (or cathode)—sandwiched around an electrolyte. Hydrogen is fed to the anode, and oxygen is fed to the cathode. Activated by a catalyst, hydrogen atoms separate into protons and electrons, which take different paths to the cathode. The electrons go through an external circuit, creating a flow of electricity. The protons migrate through the electrolyte to the cathode, where they reunite with oxygen and the electrons to produce water and heat. Fuel cells can be used to power vehicles, or to provide electricity and heat to buildings.

Representative Technologies

Hydrogen production

- Thermochemical conversion of fossil fuels, biomass, and wastes to produce hydrogen and CO_2 with the CO_2 available for sequestration (large-scale steam methane reforming is widely commercialized)
- Renewable (wind, solar, geothermal, hydro) and nuclear electricity converted to hydrogen by electrolysis of water (commercially available electrolyzers supply a small but important part of the super-high-purity hydrogen market)
- Photoelectrochemical and photobiological processes for direct production of hydrogen from sunlight and water.

Hydrogen storage
- Pressurized gas and cryogenic liquid (commercial today)
- Higher pressure (10,000 psi), carbon-wrapped conformable gas cylinders
- Cryogenic gas
- Chemically bound as metal or chemical hydrides or physically adsorbed on carbon nanostructures

Hydrogen distribution
- By pipeline (relatively significant pipeline networks exist in industrial areas of the Gulf Coast region, and near Chicago)
- By decentralized or point-of-use production using natural gas or electricity
- By truck (liquid and compressed hydrogen delivery is practiced commercially)

Hydrogen use
- Transportation sector: internal combustion engines or fuel cells to power vehicles with electric power trains. Potential long-term use as an aviation fuel and in marine applications
- Industrial sector: ammonia production, reductant in metal production, hydrotreating of crude oils, hydrogenation of oils in the food industry, reducing agent in electronics industry, etc.
- Buildings sector: combined heat, power, and fuel applications using fuel cells
- Power sector: fuel cells, gas turbines, generators for distributed power generation

Technology Applications

- In the U.S., nearly all of the hydrogen used as a chemical (i.e. for petroleum refining and upgrading, ammonia production) is produced from natural gas. The current main use of hydrogen as a fuel is by NASA to propel rockets.
- Hydrogen's potential use in fuel and energy applications includes powering vehicles, running turbines or fuel cells to produce electricity, and generating heat and electricity for buildings. The current focus is on hydrogen's use in fuel cells.

The primary fuel cell technologies under development are:

Phosphoric acid fuel cell (PAFC) - A phosphoric acid fuel cell (PAFC) consists of an anode and a cathode made of a finely dispersed platinum catalyst on carbon paper, and a silicon carbide matrix that holds the phosphoric acid electrolyte. This is the most commercially developed type of fuel cell and is being used in hotels, hospitals, and office buildings. The phosphoric acid fuel cell can also be used in large vehicles, such as buses.

Proton-exchange membrane (PEM) - The proton-exchange membrane (PEM) fuel cell uses a fluorocarbon ion exchange with a polymeric membrane as the electrolyte. The PEM cell appears to be more adaptable to automobile use than the PAFC type of cell. These cells operate at relatively low temperatures and can vary their output to meet shifting power demands. These cells are the best candidates for light-duty vehicles, for buildings, and much smaller applications.

Solid oxide fuel cells (SOFC) - Solid oxide fuel cells (SOFC) currently under development use a thin layer of zirconium oxide as a solid ceramic electrolyte, and include a lanthanum manganate cathode and a nickel-zirconia anode. This is a promising option for high-powered applications, such as industrial uses or central electricity generating stations.

Direct-methanol fuel cell (DMFC) - A relatively new member of the fuel cell family, the direct-methanol fuel cell (DMFC) is similar to the PEM cell in that it uses a polymer membrane as an electrolyte. However, a catalyst on the DMFC anode draws hydrogen from liquid methanol, eliminating the need for a fuel reformer.

Molten carbonate fuel cell (MCFC) - The molten carbonate fuel cell uses a molten carbonate salt as the electrolyte. It has the potential to be fueled with coal-derived fuel gases or natural gas.

Alkaline fuel cell - The alkaline fuel cell uses an alkaline electrolyte such as potassium hydroxide. Originally used by NASA on missions, it is now finding applications in hydrogen-powered vehicles.

Regenerative or Reversible Fuel Cells - This special class of fuel cells produces electricity from hydrogen and oxygen, but can be reversed and powered with electricity to produce hydrogen and oxygen.

Current Status

- Currently, 48% of the worldwide production of hydrogen is via large-scale steam reforming of natural gas. Today, we safely use about 90 billion cubic meters (3.2 trillion cubic feet) of hydrogen yearly.
- Direct conversion of sunlight to hydrogen using a semiconductor-based photoelectrochemical cell was recently demonstrated at 12.4% efficiency.
- Hydrogen technologies are in various stages of development across the system:

Production - Hydrogen production from conventional fossil-fuel feedstocks is commercial, and results in significant CO2 emissions. Large-scale CO2 sequestration options have not been proved and require R&D. Current commercial electrolyzers are 80-85% efficient, but the cost of hydrogen is strongly dependent on the cost of electricity. Production processes using wastes and biomass are under development, with a number of engineering scale-up projects underway.

Storage - Liquid and compressed gas tanks are available and have been demonstrated in a small number of bus and automobile demonstration projects. Lightweight, fiber-wrapped tanks have been developed and tested for higher-pressure hydrogen storage. Experimental metal hydride tanks have been used in automobile demonstrations. Alternative solid-state storage systems using alanates and carbon nanotubes are under development.

Use - Small demonstrations by domestic and foreign auto and bus companies have been undertaken. Small-scale power systems using fuel cells are being beta-tested. Small fuel cells for battery replacement applications have been developed. Much work remains.

- Recently, there have been important advances in storage energy densities in recent years: high pressure composite tanks have been demonstrated with 7.5 wt.% storage capacity, exceeding the current DOE target, and new chemical hydrides have demonstrated a reversible capacity of 5 wt.% hydrogen. The composite tank development is a successful technology partnership between the national labs, DOE and industry. Industrial investment in chemical hydride development has recently been initiated.
- SunLine Transit receives support to operate a variety of hydrogen production processes for its bus fleet. The California Fuel Cell Partnership has installed hydrogen refueling equipment (liquid delivered to the facility)
- Major industrial companies are pursuing R&D in fuel cells and hydrogen reformation technologies with a mid-term timeframe for deployment of these technologies for both stationary and vehicular applications. These companies include:

ExxonMobil	Toyota
Shell	Daimler-Chrysler
Texaco	Honda
BP	International Fuel Cells
General Motors	Ballard
Ford	Air Products
Daimler-Chrysler	Praxair
Toyota	Plug Power Systems

Technology History

- From the early 1800s to the mid 1900s, a gaseous product called town gas, manufactured from coal, supplied lighting and heating for America and Europe. Town gas is 50% hydrogen, with the rest comprised of mostly methane and carbon dioxide, with 3% to 6% carbon monoxide. Then, large natural gas fields were discovered, and networks of natural gas pipelines displaced town gas. (Town gas is still found in limited use today in Europe and Asia.)
- From 1958 to present, the National Aeronautics and Space Administration (NASA) has continued work on using hydrogen as a rocket fuel and electricity source via fuel cells. NASA became the worldwide largest user of liquid hydrogen and is renowned for its safe handling of hydrogen.

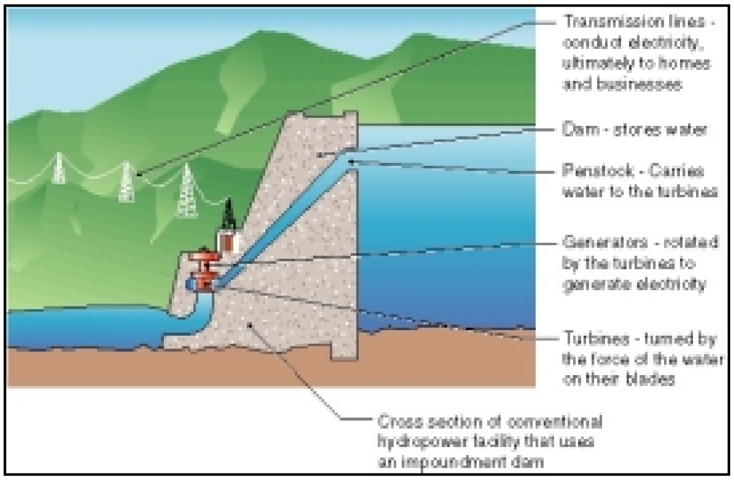
- During the 20th century, hydrogen was used extensively as a key component in the manufacture of ammonia, methanol, gasoline, and heating oil. It was and still is also used to make fertilizers, glass, refined metals, vitamins, cosmetics, semiconductor circuits, soaps, lubricants, cleaners, margarine, and peanut butter.
- Recently, (in the late 20th century/dawn of 21st century) many industries worldwide have begun producing hydrogen, hydrogen-powered vehicles, hydrogen fuel cells, and other hydrogen products. From Japan's hydrogen delivery trucks to BMW's liquid-hydrogen passenger cars, to Ballard's fuel cell transit buses in Chicago and Vancouver, B.C.; to Palm Desert's Renewable Transportation Project, to Iceland's commitment to be the first hydrogen economy by 2030; to the forward-thinking work of many hydrogen organizations worldwide, to Hydrogen Now!'s public education work; the dynamic progress in Germany, Europe, Japan, Canada, the U.S., Australia, Iceland, and several other countries launch hydrogen onto the main stage of the world's energy scene.

Technology Future

- Fuel cells are a promising technology for use as a source of heat and electricity for buildings, and as an electrical power source for electric vehicles. Although these applications would ideally run off pure hydrogen, in the near-term they are likely to be fueled with natural gas, methanol, or even gasoline. Reforming these fuels to create hydrogen will allow the use of much of our current energy infrastructure—gas stations, natural gas pipelines, etc.—while fuel cells are phased in. The electricity grid and the natural gas pipeline system will serve to supply primary energy to hydrogen producers.
- By 2005, if DOE R&D goals are met, (1) onboard hydrogen storage in metal hydrides at >5 wt% will be developed; (2) complete engineering design of a small-scale, mass-producible reformer for natural gas will be completed; and (3) an integrated biomass-to-hydrogen system will be demonstrated.
- By 2010, advances will be made in photobiological and photoelectrochemical processes for hydrogen production, efficiencies of fuel cells for electric power generation will increase, and advances will be made in fuel cell systems based on carbon structures, alanates, and metal hydrides
- Although comparatively little hydrogen is currently used as fuel or as an energy carrier, the long-term potential is for us to make a transition to a hydrogen-based economy in which hydrogen will join electricity as a major energy carrier. Furthermore, much of the hydrogen will be derived from domestically plentiful renewable energy or fossil resources, making the Hydrogen Economy synonymous with sustainable development and energy security.
- In summary, future fuel cell technology will be characterized by reduced costs and increased reliability for transportation and stationary (power) applications
- For a fully developed hydrogen energy system, a new hydrogen infrastructure/delivery system will be required.
- In the future, hydrogen could also join electricity as an important *energy carrier*. An energy carrier stores, moves, and delivers energy in a usable form to consumers. Renewable energy sources, like the sun or wind, can't produce energy all the time. The sun doesn't always shine nor the wind blow. But hydrogen can store this energy until it is needed and can be transported to where it is needed.
- Some experts think that hydrogen will form the basic energy infrastructure that will power future societies, replacing today's natural gas, oil, coal, and electricity infrastructures. They see a new *hydrogen economy* to replace our current energy economies, although that vision probably won't happen until far in the future.

Advanced Hydropower

Technology Description



Advanced hydropower is new technology for producing hydroelectricity more efficiently, with improved environmental performance. Current technology often has adverse environmental effects, such as fish mortality and changes to downstream water quality and quantity. The goal of advanced hydropower technology is to maximize the use of water for hydroelectric generation while eliminating these adverse side effects – in many cases both increased energy and improved environmental conditions can be achieved.

System Concepts

- Conventional hydropower projects use either impulse or reaction turbines to convert kinetic energy in flowing or falling water into turbine torque and power. Source water may be from free-flowing rivers/streams/canals or released from upstream storage reservoirs.
- Improvements and efficiency measures can be made in dam structures, turbines, generators, substations, transmission lines, and systems operation that will help sustain hydropower's role as a clean, renewable energy source.

Representative Technologies

- Turbine designs that minimize entrainment mortality of fish during passage through the power plant.
- Autoventing turbines to increase dissolved oxygen in discharges downstream of dams.
- Reregulating and aerating weirs used to stabilize tailwater discharges and improve water quality.
- Adjustable-speed generators producing hydroelectricity over a wider range of heads and providing more uniform instream flow releases without sacrificing generation opportunities.
- New assessment methods to balance instream flow needs of fish with water for energy production.
- Advanced instrumentation and control systems that modify turbine operation to maximize environmental benefits and energy production.

Technology Applications

- Advanced hydropower products can be applied at more than 80% of existing hydropower projects (installed conventional capacity is now 78 GW); the potential market also includes 15–20 GW at existing dams without hydropower facilities (i.e., no new dams required for development) and about 30 GW at undeveloped sites that have been identified as suitable for new dams.
- The nation's largest hydropower plant is the 7,600 megawatt Grand Coulee power station on the Columbia River in Washington State. The plant is being upscaled to 10,080 megawatts, which will place it second in the world behind a colossal 13,320 megawatt plant in Brazil.
- There would be significant environmental benefits from installing advanced hydropower technology, including enhancement of fish stocks, tailwater ecosystems, and recreational opportunities. These benefits would occur because the advanced technology reverses adverse effects of the past.
- Additional benefits would come from the protection of a wide range of ancillary benefits that are provided at hydropower projects but are at extreme risk of becoming lost in the new deregulated environment.

Current Status

- Hydropower (also called hydroelectric power) facilities in the United States can generate enough power to supply 28 million households with electricity, the equivalent of nearly 500 million barrels of oil. The total U.S. hydropower capacity—including pumped storage facilities—is about 95,000 megawatts. Researchers are working on advanced turbine technologies that will not only help maximize the use of hydropower but also minimize adverse environmental effects.
- According to EIA, hydropower provided 12.6% of the nation's electricity generating capability in 1999 and 80% of the electricity produced from renewable energy sources.
- DOE estimates current capital costs for large hydropower plants to be $1,700 to $2,300 per kW (although no new plants are currently being built in the U.S. and O&M is estimated at approximately 0.7 cents/kWh.
- Worldwide, hydropower plants have a combined capacity of 675,000 megawatts and annually produce over 2.3 trillion kilowatt-hours of electricity, the energy equivalent of 3.6 billion barrels of oil.
- Existing hydropower generation is declining because of a combination of real and perceived environmental problems, regulatory pressures, and changes in energy economics (deregulation, etc.); potential hydropower resources are not being developed for similar reasons.
- The current trend is to replace hydropower with electricity from fossil fuels.
- Some new, environmentally friendly technologies are being implemented (e.g., National Hydropower Association's awards for Outstanding Stewardship of America's Rivers).
- DOE's Advanced Hydropower Turbine System (AHTS) program is also demonstrating that new turbine designs are feasible, but additional support is needed to fully evaluate these new designs in full-scale applications.
- There is insufficient understanding of how fish respond to turbulent flows in draft tubes and tailraces to support biological design criteria for those zones of power plants.
- Fish resource management agencies do not recognize that the route through turbines is acceptable for fish – this perception could be overcome if field testing continues to show mortality through turbines is not greater than other passage routes.
- TVA's Lake Improvement Plan has demonstrated that improved turbine designs can be implemented with significant economic and environmental benefits.
- Field testing of the Minimum Gap Runner (MGR) designs for Kaplan turbines indicate that fish survival up to 98% is possible, if conventional turbines are modified.
- FERC instituted a short-term reduction in regulatory barriers on the West Coast in 2001 – this resulted in more than 100,000 MWh of additional generation and a significant shift from non-peak to peak production, without significant adverse environmental effects.
- Regulatory trends in relicensing are to shift operation from peaking to baseload, effectively reducing the energy value of hydroelectricity; higher instream flow requirements are also reducing total energy production to protect downstream ecosystems, but scientific justification is weak.
- Frequent calls for dam removal is making relicensing more costly to dam owners.
- Regional efforts by Army Corps of Engineers and Bonneville Power Administration are producing some site-specific new understanding, especially in the Columbia River basin, but commercial applications are unlikely because of pressures from industry deregulation and environmental regulation.
- Voith-Siemans Hydro and TVA have established a limited partnership to market environmentally friendly technology at hydropower facilities. Their products were developed in part by funding provided by DOE and the Corps of Engineers, as well as private sources.
- Flash Technology is developing strobe lighting systems to force fish away from hydropower intakes and to avoid entrainment mortality in turbines.

Technology History
• Since the time of ancient Egypt, people have used the energy in flowing water to operate machinery and grind grain and corn. However, hydropower had a greater influence on people's lives during the 20th century than at any other time in history. Hydropower played a major role in making the wonders of electricity a part of everyday life and helped spur industrial development. Hydropower continues to produce 24% of the world's electricity and supply more than 1 billion people with power. • The first hydroelectric power plant was built in 1882 in Appleton, Wisconsin, to provide 12.5 kilowatts to light two paper mills and a home. Today's hydropower plants generally range in size from several hundred kilowatts to several hundred megawatts, but a few mammoth plants have capacities up to 10,000 megawatts and supply electricity to millions of people. • By 1920, 25% electrical generation in the U.S. was from hydropower, and was 40% in 1940. • Most hydropower plants are built through federal or local agencies as part of a multipurpose project. In addition to generating electricity, dams and reservoirs provide flood control, water supply, irrigation, transportation, recreation and refuges for fish and birds. Private utilities also build hydropower plants, although not as many as government agencies.
Technology Future
• By 2003, a quantitative understanding of the responses of fish to multiple stresses inside a turbine should be developed. Biological performance criteria for use in advanced turbine design should also be available. • By 2005, environmental mitigation studies should be available on topics such as in-stream flow needs to produce more efficient and less controversial regulatory compliance. In addition, pilot-scale testing of new runner designs, including field evaluation of environmental performance, will allow full-scale prototype construction and testing to proceed. • By 2010, full-scale prototype testing of AHTS designs should be completed, including verified biological performance of AHTS in the field. This will allow AHTS technology to be transferred to the market.

Hydroelectric Power

Market Data

Cumulative Grid Connected Hydro Capacity (MW)*

Source: U.S. data from *EIA, AEO 1998-2002- Tables A9 and A17, Renewable Resources in the Electric Supply, 1993- Table 4. World Total from EIA, International Energy Annual, 1996-1999, Table 6.4. International data from International Energy Agency, Electricity Information 1997 (1998 edition).*

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
U.S.									
Conventional and other Hydro			72,900	78,480	78,390	78,530	79,110	80,280	80,270
Pumped Storage				19,900	19,600	19,600	19,300	19,200	19,200
U.S. Hydro Total				98,380	97,990	98,130	98,410	99,480	99,470
OECD Europe	119,650	126,500	132,270	134,190	134,440				
IEA Europe	118,450	125,100	130,740	131,730	132,000				
Japan	18,280	19,980	20,820	21,160	21,210				
OECD Total	278,310	309,220	324,530	321,520	321,380				
IEA Total	271,060	301,210	315,130	308,160	307,420				
World Total					656,000	667,000	678,000	683,000	

*excludes pumped storage, except for specific U.S. pumped storage capacity listed.

Annual Generation from Cumulative Installed Capacity (Billion kWh)

Source: EIA, International Energy Annual 1999, DOE/EIA-0219(99), Table 1.5.

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
United States	300	325	298	334	376	376	339	324	
Canada	251	301	294	332	352	347	329	340	
Mexico	17	26	23	27	31	26	24	32	
Japan	88	82	88	81	80	89	92	85	
Western Europe	393	417	411	447	423	440	454	466	
Former Soviet Union	184	205	231	238	215	216	224	226	

	1980	1985	1990	1995	1996	1997	1998	1999	2000
Eastern Europe	55	50	43	56	60	58	61	59	
China	58	91	125	184	185	193	203	223	
Brazil	128	177	205	251	263	276	288	306	
Rest of World	284	341	459	550	559	571	573	565	
World Total	1,758	2,015	2,176	2,501	2,543	2,594	2,587	2,626	

State Generating Capability (MW)

Source: *EIA, Electric Power Annual Vol.1: 1994 & 1999-2000- Table 2, 1995-1997- Table 5.*

Top Ten States	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Washington				21,054	21,038	21,054			
Oregon				9,021	9,031	9,038			
California				13,504	13,538	13,535			
New York				7,246	7,311	5,279			
Montana				2,514	2,551	2,546			
Idaho				2,416	2,418	2,432			
Arizona				2,833	2,884	2,884			
Alabama				2,959	2,962	2,881			
South Dakota				1,820	1,820	1,820			
Tennessee				3,668	3,744	3,725			
U.S. Total			90,885	96,629	96,342	94,477	98,471	99,041	99,068

State Annual Generation from Cumulative Installed Capacity* (Billion kWh)

Source: *EIA, Electric Power Annual Vol. 1: 1998-2000- Table A12, 1996-1997- Table 10.*

Top Ten States	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Washington				82.0	98.1	103.6	79.8	97.0	80.5
Oregon				40.4	44.5	46.3	39.9	45.6	38.2
California				47.4	44.1	39.8	50.8	40.4	39.2
New York				23.6	26.0	27.9	28.2	23.6	24.2
Montana				10.7	13.7	13.3	11.1	13.8	12.1
Idaho				10.1	12.2	13.5	12.9	13.4	11.0
Arizona				8.5	9.5	12.4	11.2	10.1	8.6
Alabama				9.5	11.1	11.5	10.6	7.8	5.8

South Dakota	6.0	8.0	9.0	5.8	6.7	5.7
Tennessee	8.2	9.9	9.4	10.2	7.2	5.7
U.S. Total	294	328	337	319	313	273

* Annual generation figures for years before 1998 do not include nonutility generation, which is not reported in the Electric Power Annual.

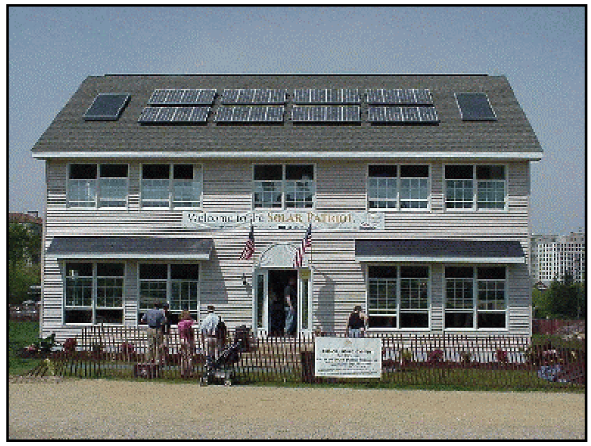
Solar Buildings

Technology Description

Solar building technologies deliver heat, electricity, light, hot water, and cooling to residential and commercial buildings. By combining solar thermal and electric building technologies with very energy-efficient construction methods, lighting, and appliances, it is possible to build “Zero Energy Homes” (see photo for an example demonstration home). Zero Energy Buildings (residential and commercial) have a zero net need for offsite energy on an annual basis and also have no carbon emissions.

System Concepts

- In solar heating systems, solar thermal collectors convert solar energy into heat at the point of use, usually for domestic hot water and space heating.
- In solar cooling systems, solar thermal collectors convert solar energy into heat for absorption chillers or desiccant regeneration.
- In solar lighting systems, sunlight is transmitted into the interior of buildings using glazed apertures, light pipes, and/or optical fibers.



Representative Technologies

- Active solar heating systems use pumps and controls to circulate a heat transfer fluid between the solar collector(s) and storage. System sizes can range from 1 to 100 kW.
- Passive solar heating systems do not use pumps and controls but rather rely on natural circulation to transfer heat into storage. System sizes can range from 1 to 10 kW.
- Transpired solar collectors heat ventilation air for industrial and commercial building applications. A transpired collector is a thin sheet of perforated metal that absorbs solar radiation and heats fresh air drawn through its perforations.
- Hybrid solar lighting systems focus concentrated sunlight on optical fibers in order to combine natural daylight with conventional illumination. Hybrid Solar Lighting (HSL) has the potential to more than double the efficiency and affordability of solar energy in commercial buildings by simultaneously separating and using different portions of the solar energy spectrum for different end-use purposes, i.e. lighting and distributed power generation.

Technology Applications

- More than 1,000 MW of solar water-heating systems are operating successfully in the United States, generating more than 3 million MW-hrs per year.
- Based on peer-reviewed market penetration estimates, there will be approximately 1 million new solar water-heating systems installed by 2020, offering an energy savings of 0.16 quads (164 trillion Btus).
- Retrofit markets: There are 72.5 million existing single-family homes in the United States. An estimate of the potential replacement market of 29 million solar water-heating systems assumes that only 40% of these existing homes have suitable orientation and nonshading. (9.2 million replacement electric and gas water heaters.)
- New construction: In 2000, 1.2 million new single-family homes were built in the United States. Assuming 70% of these new homes could be sited to enable proper orientation of solar water- heating systems, this presents another 840,000 possible system installations annually.
- While the ultimate market for the zero-energy building concept is all new building construction; the near-term focus is on residential buildings; particularly, single-family homes in the Sunbelt areas of the

country. Of the 1.2 million new single-family homes built in the U.S. in 2000, 44% of these new homes were in the southern region of the country and 25% were in the western region, both areas with favorable solar resources.

Current Status

- About 1.2 million solar water-heating systems have been installed in the U.S., mostly in the 1970s and 1980s. Due to relatively low energy prices and other factors, there are approximately only 8,000 installations per year.
- Typical residential solar systems use glazed flat-plate collectors combined with storage tanks to provide 40% to 70% of residential water-heating requirements. Typical systems generate 2500 kWh of energy per year and cost $1.00 to $2.00/Watt.
- Typical solar pool-heating systems use unglazed polymer collectors to provide 50% to 100% of residential pool-heating requirements. Typical systems generate 1,600 therms or 46,000 kWh of energy per year and cost $0.30 to $0.50/Watt
- Four multidisciplinary homebuilding teams have begun the initial phase of designing and constructing "Zero Energy Homes" for various new construction markets in the United States. One homebuilder – Shea Homes in San Diego – is currently building, and quickly selling, 300 houses with Zero Energy Home features – solar electric systems, solar water heating, and energy-efficient construction.
- Key companies developing or selling solar water heaters include:

Alternative Energy Technologies	Harter Industries
Aquatherm	Duke Solar
FAFCO	Heliodyne, Inc.
Radco Products	Sun Earth
Sun Systems	Thermal Conversion Technologies

Technology History

- 1890s- First commercially available solar water heaters produced in southern California. Initial designs were roof-mounted tanks and later glazed tubular solar collectors in thermosiphon configuration. Several thousand systems were sold to homeowners.
- 1900s- Solar water heating technology advanced to roughly its present design in 1908 when William J. Bailey of the Carnegie Steel Company, invented a collector with an insulated box and copper coils.
- 1940s- Bailey sold 4,000 units by the end of W.W.I and a Florida businessperson who bought the patent rights sold nearly 60,000 units by 1941.
- 1950s- Industry virtually expires due to inability to compete against cheap and available natural gas and electric service.
- 1970s- The modern solar industry began in response to the OPEC oil embargo in 1973-74, with a number of federal and state incentives established to promote solar energy. President Jimmy Carter put solar water-heating panels on the White House. FAFCO, a California company specializing in solar pool heating, and Solaron, a Colorado company that specialized in solar space and water heating, became the first national solar manufacturers in the United States. In 1974, more than 20 companies started production of flat-plate solar collectors, most using active systems with antifreeze capabilities. Sales in 1979 were estimated at 50,000 systems. In Israel, Japan, and Australia, commercial markets and manufacturing had developed with fairly widespread use.
- 1980s- In 1980, the Solar Rating and Certification Corp (SRCC) was established for testing and certification of solar equipment to meet set standards. In 1984, the year before solar tax credits expired, an estimated 100,000-plus solar hot-water systems were sold. Incentives from the 1970s helped create the 150 business manufacturing industry for solar systems with more than $800 million in

annual sales by 1985. When the tax credits expired in 1985, the industry declined significantly. During the Gulf War, sales again rose by about 10 to 20% to its peak level, more than 11,000 square feet per year (sq.ft./yr) in 1989 and 1990.

- 1990s- Solar water-heating collector manufacturing activity declined slightly, but has hovered around 6,000 to 8,000 sq.ft./yr. Today's industry represents the few strong survivors: More than 1.2 million buildings in the United States have solar water heating systems, and 250,000 solar-heated swimming pools exist. Unglazed, low-temperature solar water heaters for swimming pools have been a real success story, with more than a doubling of growth in square footage of collectors shipped from 1995 to 2001.

Reference: American Solar Energy Society and Solar Energy Industry Association

Technology Future

- Near-term solar heating and cooling RD&D goals are to reduce the costs of solar water heating systems to 4¢/kWh from their current cost of 8¢/kWh using polymer materials and manufacturing enhancements. This corresponds to a 50% reduction in capital cost.
- Near-term Zero Energy Building RD&D goals are to reduce the annual energy bill for an average size home to $600 by 2004.
- Near-term solar lighting RD&D goals are to reduce the costs of solar lighting systems to 5¢/kWh.
- Zero-energy building RD&D efforts are targeted to optimize various energy efficiency and renewable energy combinations, integrate solar technologies into building materials and the building envelope, and incorporate solar technologies into building codes and standards.
- Solar heating and cooling RD&D efforts are targeted to reduce manufacturing and installation costs, improve durability and lifetime, and provide advanced designs for system integration.

Solar Buildings

Market Data

U.S. Installations (Thousands of Sq. Ft.) — Source: EIA, *Renewable Energy Annual 1997- 2000- Table 16, REA 1996- Table 18, and REA 2000- Table 8.*

	1980	1985	1990	1995	1996	1997	1998	1999	2000
Annual									
DHW					765	595	462	373	
Pool Heaters					6,787	7,528	7,200	8,141	
Total Solar Thermal	18,283	19,166	11,021	7,136	7,162	7,759	7,396	8,046	
Cumulative									
DHW									
Pool Heaters									
Total Solar Thermal	62,829	153,035	199,459	233,386	241,002	249,139	256,895	265,748	

U.S. Annual Shipments (Thousand Sq. Ft.) — Source: *Energy Information Administration, Renewable Energy Annual 1997- Table 11, REA 1996 Table 16 and REA 2000 Table 9.*

	1980	1985	1990	1995	1996	1997	1998	1999	2000
Total	19,398		11,409	7,666	7,616	8,138	7,756	8,583	
Imports			1,562	2,037	1,930	2,102	2,206	2,352	
Exports	1,115		245	530	454	379	360	537	

U.S. Shipments by Cell Type (thousands of sq. ft.) — Source: *EIA Renewable Energy Annual 2000. Table 10.3 Solar Thermal Collector Shipments by Type, Price, and Trade, 1974-1999.*

	1980	1985	1990	1995	1996	1997	1998	1999	2000
Low Temperature Collectors	12,233		3,645	6,813	6,821	7,524	7,292	8,152	
Medium Temperature Collectors	7,165		2,527	840	785	606	443	427	
High Temperature Collectors			5,237	13	10	7	21	4	
Total	19,398		11,409	7,666	7,616	8,137	7,756	8,583	

U.S. Shipments of All Solar Thermal Collectors by Market Sector, and End Use (Thousands of Sq. Ft.)	Source: EIA, *Renewable Energy Annual 1997, 1999- 2000- Table 16, and REA 1998- Table 19.*							
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Market Sector									
Residential					6,874	7,360	7,165	7,773	
Commercial					682	768	517	785	
Industrial					54	7	62	18	
Utility					0	0	2	4	
Other					7	2	3	2	
Total					7,618	8,137	7,749	8,582	
End Use									
Pool Heating					6,787	7,528	7,200	8,141	
Hot Water					765	595	462	373	
Space Heating					57	9	66	42	
Space Cooling					0	0	0	0	
Combined Space and Water Heating					2	3	16	16	
Process Heating					3	0	0	5	
Electricity Generation					0	0	2	4	
Other					0	1	2	2	
Total					7,615	8,136	7,748	8,583	

U.S. Shipments of High Temperature Collectors by Market Sector, and End Use (Thousands of Sq. Ft.)	Source: EIA, *Renewable Energy Annual 1997, 1999- 2000- Table 16, and REA 1998- Table 19.*							
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Market Sector									
Residential					0	0	0	0	
Commercial					7	7	18	0	
Industrial					2	0	0	0	

Utility					0	0	2	4	
Other					0	0	1	0	
Total					10	7	21	4	
End Use									
Pool Heating					0	0	0	0	
Hot Water					7	7	18	0	
Space Heating					0	0	0	0	
Space Cooling					0	0	0	0	
Combined Space and Water Heating					0	0	0	0	
Process Heating					2	0	0	0	
Electricity Generation					0	0	2	4	
Other					0	0	1	0	
Total					10	7	21	4	

U.S. Shipments of Medium Temperature Collectors by Market Sector, and End Use (Thousands of Sq. Ft.)

Source: EIA, *Renewable Energy Annual 1997, 1999- 2000- Table 16, and REA 1998- Table 19.*

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Market Sector									
Residential					728	569	355	365	
Commercial					50	35	70	59	
Industrial					1	0	18	0	
Utility					0	0	0	0	
Other					7	2	0	2	
Total					786	606	443	426	
End Use									
Pool Heating					21	11	36	12	
Hot Water					754	588	384	373	
Space Heating					6	2	13	24	
Space Cooling					0	0	0	0	
Combined Space and Water Heating					2	3	8	16	

	1980	1985	1990	1995	1996	1997	1998	1999	2000
Process Heating					1	0	0	0	
Electricity Generation					0	0	0	0	
Other					0	1	1	2	
Total					784	605	442	427	

U.S. Shipments of Low Temperature Collectors by Market Sector, and End Use (Thousands of Sq. Ft.)

Source: EIA, *Renewable Energy Annual 1997, 1999- 2000- Table 16, and REA 1998- Table 19.*

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Market Sector									
Residential					6,146	6,791	6,810	7,408	
Commercial					625	726	429	726	
Industrial					51	7	44	18	
Utility					0	0	0	0	
Other					0	0	2	0	
Total					6,822	7,524	7,285	8,152	
End Use									
Pool Heating					6,766	7,517	7,164	8,129	
Hot Water					4	0	60	0	
Space Heating					51	7	53	18	
Space Cooling					0	0	0	0	
Combined Space and Water Heating					0	0	8	0	
Process Heating					0	0	0	5	
Electricity Generation					0	0	0	0	
Other					0	0	0	0	
Total					6,821	7,524	7,285	8,152	

Technology Performance

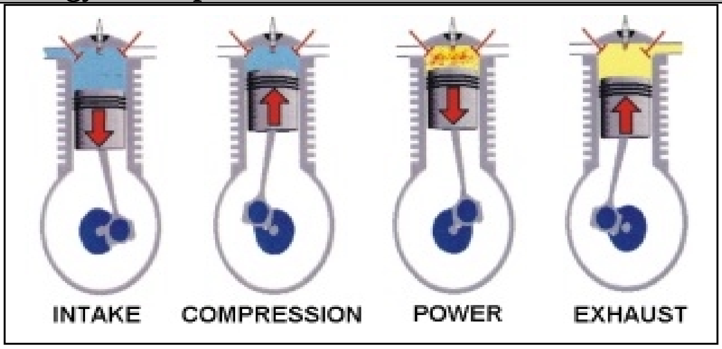
Energy Production	Source: *Arthur D. Little, Review of FY 2001 Office of Power Technology's Solar Buildings Program Planning Unit Summary, December 1999.*								
	1980	**1985**	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
Energy Savings									
DHW (kWh/yr)					2,750				
Pool Heater (therms/yr)					1,600				

Cost	Source: *Hot Water Heater data from Arthur D. Little, Water Heating Situation Analysis, November 1996, page 53, and Pool Heater data from Ken Sheinkopf, Solar Today, Nov/Dec 1997, pp. 22-25.*								
	1980	**1985**	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
Capital Cost* ($/System)									
Domestic Hot Water Heater					1,900 - 2,500				
Pool Heater					3,300 - 4,000				
O&M ($/System-yr)									
Domestic Hot Water Heater					25 - 30				
Pool Heater					0				

* Costs represent a range of technologies, with the lower bounds representing advanced technologies, such as a low-cost polymer integral collector for domestic hot-water heaters, which are expected to become commercially available after 2010.

Reciprocating Engines

Technology Description



Reciprocating engines, also known as internal combustion engines, require fuel, air, compression, and a combustion source to function. They make up the largest share of the small power generation market and can be used in a variety of applications due to their small size, low unit costs, and useful thermal output.

System Concepts

Reciprocating engines fall into one of two categories depending on the ignition source: spark ignition (SI), typically fueled by gasoline or natural gas; or compression ignition (CI), typically fueled by diesel oil.

Reciprocating engines also are categorized by the number of revolutions it takes to complete a combustion cycle. A two-stroke engine completes its combustion cycle in one revolution and a four-stroke engine completes the combustion process in two revolutions.

Representative Technologies

The four-stroke SI engine has an intake, compression, power, and exhaust cycle. In the intake stroke, as the piston moves downward in its cylinder, the intake valve opens and the upper portion of the cylinder fills with fuel and air. When the piston returns upward in the compression cycle, the spark plug fires, igniting the fuel/air mixture. This controlled combustion forces the piston down in the power stroke, turning the crankshaft and producing useful shaft power. Finally the piston moves up again, exhausting the burnt fuel and air in the exhaust stroke.

The four-stroke CI engine operates in a similar manner, except diesel fuel and air ignite when the piston compresses the mixture to a critical pressure. At this pressure, no spark or ignition system is needed since the mixture ignites spontaneously, providing the energy to push the piston down in the power stroke.

The two-stroke engine, whether SI or CI, has a higher power density, because it requires half as many crankshaft revolutions to produce power. However, two-stroke engines are prone to let more fuel pass through, resulting in higher hydrocarbon emissions in the form of unburned fuel.

Technology Applications

Reciprocating engines can be installed to accommodate baseload, peaking, or standby power applications. Commercially available engines range in size from 50 kW to 6.5 MW making them suitable for many distributed power applications. Utility substations and small municipalities can install engines to provide baseload or peak shaving power. However, the most promising markets for reciprocating engines are on-site at commercial, industrial, and institutional facilities. With fast start-up time, reciprocating engines can play integral back-up roles in many building energy systems. Onsite reciprocating engines become even more attractive in regions with high electric rates (energy/demand charges).

When properly treated the engines can run on fuel generated by waste treatment (methane) and other biofuels.

By using the recuperators that capture and return waste exhaust heat, reciprocating engines can be used in combined heat and power (CHP) systems to achieve energy efficiency levels approaching 80%. In fact, reciprocating engines make up a large portion of the CHP or cogeneration market.

Current Status

Commercially available engines have electrical efficiencies (LHV) between 37 and 40% and yield NOx emissions of 1-2 grams per horsepower hour (hp-hr).
Installed cost for reciprocating engines range between $600 and $1,600/ kW depending on size and whether the unit is for a straight generation or cogeneration application. Operating and maintenance costs range 2 cents to 2.5 cents/kWh.
Exhaust temperature for most reciprocating engines is 700-1200° F in non-CHP mode and 350-500°F in a CHP system after heat recovery.
Noise levels with sound enclosures are typically between 70-80 dB.
The reciprocating engine systems typically include several major parts: fuel storage, handling, and conditioning, prime mover (engine), emission controls, waste recovery (CHP systems) and rejections (radiators), and electrical switchgear.
Annual shipments of reciprocating engines (sized 10GW or less) have almost doubled to 18 GW between 1997 and 2000. The growth is overwhelming in the diesel market, which represented 16 GW shipments compared with 2 GW of natural gas reciprocating engine shipments in 2000 (*Source: Diesel and Gas Turbine Worldwide*).
Key indicators for stationary reciprocating engines:

Installed Worldwide Capacity	Installed US Capacity	Number of CHP sites using Recips in the U.S.
146 GW	52 GW	1,022

Source: Distributed Generation: The Power Paradigm for the New Millenium, 2001

Manufacturers of reciprocating engines include:

Caterpillar	Jenbacher
Cummins	Wartsila
Detroit Diesel	Waukesha

Technology History

Natural gas reciprocating engines have been used for power generation since the 1940s. The earliest engines were derived from diesel blocks and incorporated the same components of the diesel engine. Spark plugs and carburetors replaced fuel injectors, and lower compression–ratio pistons were substituted to run the engine on gaseous fuels. These engines were designed to run without regard to fuel efficiency or emission levels. They were used mainly to produce power at local utilities and to drive pumps and compressors.
In the mid-1980s, manufacturers were facing pressure to lower NOx emissions and increase fuel economy. Leaner air-fuel mixtures were developed using turbochargers and charge air coolers, and in combination with lower in-cylinder fire temperatures, the engines reduced NOx from 20 to 5 g/bhp-hr. The lower in-cylinder fire temperatures also meant that the BMEP (Brake Mean Effective Pressure) could increase without damaging the valves and manifolds.
Reciprocating engine sales have grown more then five-fold from 1988 (2 GW) to 1998 (11.5 GW). Gas-fired engine sales in 1990 were 4% compared to 14% in 1998. The trend is likely to continue for gas-fired reciprocating engines due to strict air-emission regulations and because performance has been steadily improving for the past 15 years.

Technology Future
The U.S. Department of Energy, in partnership with the Gas Technology Institute, the Southwest Research Institute, and equipment manufacturers, supports the Advanced Reciprocating Engines Systems (ARES) consortium, aimed at further advancing the performance of the engine. Performance targets include: *High Efficiency*- Target fuel-to-electricity conversion efficiency (LHV) is 50 % by 2010. *Environment* – Engine improvements in efficiency, combustion strategy, and emissions reductions will substantially reduce overall emissions to the environments. The NOx target for the ARES program is 0.1 g/hp-hr, a 90% decrease from today's NOx emissions rate. *Fuel Flexibility* – Natural gas-fired engines are to be adapted to handle biogas, renewables, propane and hydrogen, as well as dual fuel capabilities. *Cost of Power* – The target for energy costs, including operating and maintenance costs is 10 % less than current state-of-the-art engine systems. *Availability, Reliability, and Maintainability* – The goal is to maintain levels equivalents to current state-of-the-art systems. Other R&D directions include: new turbocharger methods, heat recovery equipment specific to the reciprocating engine, alternate ignition system, emission control technologies, improved generator technology, frequency inverters, controls/sensors, higher compression ratio, and dedicated natural gas cylinder heads.

Reciprocating Engines

Technology Performance

Power Ranges (kW) of Selected Manufacturers — Source: Manufacturer Specs

	Low	*High*
Caterpillar	150	3,350
Waukesha	200	2,800
Cummins	5	1,750
Jenbacher	200	2,600
Wartsila	500	5,000

Market Data

Market Shipments
(GW of units under 10 MW in size)

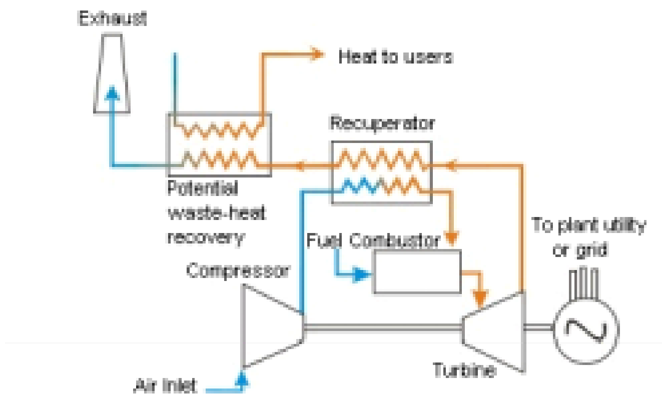
Source: Debbie Haught, DOE, communication 2/26/02 - from Diesel and Gas Turbine Worldwide.

	1996	1997	1998	1999	2000
Diesel Recips	7.96	7.51	8.23	10.02	16.46
Gas Recips	0.73	1.35	1.19	1.63	2.07

Microturbines

Technology Description

Microturbines are small combustion turbines of a size comparable to a refrigerator and with outputs of 25 kW to 500 kW. They are used for stationary energy generation applications at sites with space limitations for power production. They are fuel-flexible machines that can run on natural gas, biogas, propane, butane, diesel, and kerosene. Microturbines have few moving parts, high efficiency, low emissions, low electricity costs, and waste heat utilization opportunities; and are lightweight and compact in size. Waste heat recovery can be used in combined heat and power (CHP) systems to achieve energy efficiency levels greater than 80 percent.



System Concepts

- Microturbines consist of a compressor, combustor, turbine, alternator, recuperator, and generator.
- Microturbines are classified by the physical arrangement of the component parts: single shaft or two-shaft, simple cycle or recuperated, inter-cooled, and reheat. The machines generally operate over 40,000 rpm.
- A single shaft is the more common design as it is simpler and less expensive to build. Conversely, the split shaft is necessary for machine-drive applications, which do not require an inverter to change the frequency of the AC power.
- Efficiency gains can be achieved with greater use of materials like ceramics, which perform well at higher engine operating temperatures.

Representative Technologies

- Microturbines in a simple cycle, or unrecuperated, turbine; compressed air is mixed with fuel and burned under constant pressure conditions. The resulting hot gas is allowed to expand through a turbine to perform work. Simple-cycle microturbines have lower cost, higher reliability, and more heat available for CHP applications than recuperated units.
- Recuperated units use a sheet-metal heat exchanger that recovers some of the heat from an exhaust stream and transfers it to the incoming air stream. The preheated air is then used in the combustion process. If the air is preheated, less fuel is necessary to raise its temperature to the required level at the turbine inlet. Recuperated units have a higher efficiency and thermal-to-electric ratio than unrecuperated units, and yield 30-40 percent fuel savings from preheating.

Technology Applications

Microturbines can be used in a wide range of applications in the commercial, industrial, and institutional sectors, microgrid power parks, remote off-grid locations, and premium power markets.

Microturbines can be used for backup power, baseload power, premium power, remote power, cooling and heating power, mechanical drive, and use of wastes and biofuels.

Microturbines can be paired with other distributed energy resources such as energy storage devices and thermally activated technologies.

Current Status

- Microturbine systems are just entering the market and the manufacturers are targeting both traditional and nontraditional applications in the industrial and buildings sectors, including CHP, backup power, continuous power generation, and peak shaving.
- The most popular microturbine installed to date is the 30-kW system manufactured by Capstone.
- The typical 30-60 kW unit cost averages $1,000/kW. For gas-fired microturbines, the present installation cost (site preparation and natural gas hookup) for a typical commercial site averages $8,200.
- Honeywell pulled out of the microturbine business in December 2001, leaving the following manufacturers in the microturbine market:

Capstone Turbine Corporation	Ingersoll-Rand
DTE Energy Technologies	UTRC
Elliot Energy Systems	Bowman Power
Turbec	

- Capstone, Ingersoll-Rand, Elliott, and Turbec combined have shipped more than 2,100 units (156 MW) worldwide during the past four years.

Technology History

Microturbines represent a relatively new technology, which is just making the transition to commercial markets. The technology used in microturbines is derived from aircraft auxiliary power systems, diesel engine turbochargers, and automotive designs.

In 1988, Capstone Turbine Corporation began developing the microturbine concept; and in 1998, Capstone was the first manufacturer to offer commercial power products utilizing microturbine technology.

Technology Future

- The market for microturbines is expected to range from $2.4-to-$8 billion by 2010, with 50 percent of sales concentrated in North America.
- The acceptable cost target for microturbine energy is $0.05/kWh, which would present a cost advantage over most nonbaseload utility power.
- The next generation of "ultra-clean, high efficiency" microturbine product designs will focus on the following DOE performance targets:
  - High Efficiency — Fuel-to-electricity conversion efficiency of at least 40 percent.
  - Environment — NOx < 7 ppm (natural gas).
  - Durability — 1,000 hours of reliable operations between major overhauls and a service life of at least 45,000 hours.
  - Cost of Power — System costs < $500/kW, costs of electricity that are competitive with alternatives (including grid) for market applications by 2005 (for units in the 30-60 kW range)
  - Fuel Flexibility — Options for using multiple fuels including diesel, ethanol, landfill gas, and biofuels.

Microturbines

Market Data

Microturbine Shipments	Source: Debbie Haught, communications 2/26/02. Capstone sales reported in Quarterly SEC filings, others estimated.			
# of units	**1998**	**1999**	**2000**	**2001**
Capstone	2	211	790	1033
Other Manufacturers				120
MW				
Capstone		6	23.7	38.1
Other Manufacturers				10.2

Technology Performance

Source: Manufacturer Surveys, Arthur D. Little (ADL) estimates.

Current System Efficiency (%)	LHV: 17-20% unrecuperated, 25-30%+ recuperated	
Lifetime (years)	5-10 years, depending on duty cycle	
Emissions (natural gas fuel)	Current	Future (2010
CO_2	670 - 1,180 g/kWh (17-30% efficiency)	
SO_2	Negligible (natural gas)	Negligible
NO_x	9-25 ppm	<9 ppm
CO	25-50 ppm	<9 ppm
PM	Negligible	Negligible
Typical System Size	Current Products: 25-100 kW Units can be bundled or "ganged" to produce power in larger increments	Future Products: up to 1 MW
Maintenance Requirements (Expected)	10,000-12,000 hr before major overhaul (rotor replacement)	
Footprint [ft^2/kW]	0.2-0.4	

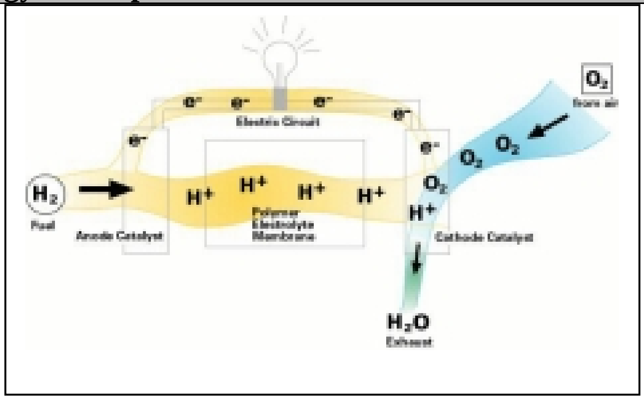
Technology Performance

Sources: Debbie Haught, DOE, communication 2/26/02 and Energetics, Inc. *Distributed Energy Technology Simulator: Microturbine Validation*, July 12 2001.

	Capstone Turbine Corporation		Elliot Energy Systems	Ingersoll-Rand Energy Services		Turbec	DTE Energy Technologies
Model Name	Model 330	Capstone 60	TA-80	PowerWorks			ENT 400 recuperated
Size	30 kW	60 kW	80 kW	70 kW		100 kW	300 kW
Voltage	400-480 VAC					400 VAC	480/277 VAC
Fuel Flexibility	natural gas, medium Btu gas, diesel, kerosene		natural gas	natural gas		natural gas, biogas, ethanol, diesel	natural gas (diesel, propane future)
Fuel Efficiency (cf/kWh)	13.73	14.23				11.2	
Efficiency	26% (+/-2%)	28% (+/- 2%)	28%	30-33%		30%	28% (+/- 2%)
	70-90% CHP	70-90% CHP	80% CHP			80% CHP	74% CHP
Emissions	NO_x <9ppmV @15% O_2		NO_x diesel <60ppm, NO_x NG <25ppm, CO diesel <400ppm, CO NG <85ppm	NO_x <9ppmV @15% O_2, CO <9ppmV @15% O_2		NO_x <15ppmV @15% O_2, CO <15ppm, UHC <10ppm	NOx <9ppmV @15% O_2
Units Sold	1999: 211 units			2000: 2 pre-commercial units, expected commercial in 2001		2000: 20 units in the European market	Available late 2001
	2000: 790 units						
	2001: 1,033 units		2001: 100 units				
Unit Cost	$1000/kW					$75,000	
Cold Start-Up Time	3 min						3 min emergency, 7 min normal
Web site	www.capstone.com		www.elliott-turbo.com/new/products_microtubines.html	ww.irco.com/energysystems/powerworks.html		www.turbec.com	www.dtetech.com/energynow/portfolio/2_1_4.asp

Fuel Cells

Technology Description



A fuel cell is an electrochemical energy conversion device that converts hydrogen and oxygen into electricity and water. This unique process is practically silent, nearly eliminates emissions, and has no moving parts.

System Concepts

Similar to a battery, fuel cells have an anode and a cathode separated by an electrolyte. Hydrogen enters the anode and air (oxygen) enters the cathode. The hydrogen and oxygen are separated into ions and electrons, in the presence of a catalyst. Ions are conducted through the electrolyte while the electrons flow through the anode and the cathode via an external circuit. The current produced can be utilized for electricity. The ions and electrons then recombine, with water and heat as the only byproducts.

Fuel cell systems today typically consist of a fuel processor, fuel cell stack, and power conditioner. The fuel processor, or reformer, converts hydrocarbon fuels to a mixture of hydrogen-rich gases and, depending upon the type of fuel cell, can remove contaminants to provide pure hydrogen. The fuel cell stack is where the hydrogen and oxygen electrochemically combine to produce electricity. The electricity produced is direct current (DC) and the power conditioner converts the DC electricity to alternating current (AC) electricity, for which most of the end-use technologies are designed. As a hydrogen infrastructure emerges, the need for the reformer will disappear as pure hydrogen will be available near point of use.

Representative Technologies

Fuel cells are categorized by the kind of electrolyte they use.

Alkaline Fuel Cells (AFCs) were the first type of fuel cell to be used in space applications. AFCs contain a potassium hydroxide (KOH) solution as the electrolyte and operate at temperatures between 60 and 250°C (140 to 482°F). The fuel supplied to an AFC must be pure hydrogen. Carbon monoxide poisons an AFC, and carbon dioxide (even the small amount in the air) reacts with the electrolyte to form potassium carbonate.

Phosphoric Acid Fuel Cells (PAFCs) were the first fuel cells to be commercialized. These fuel cells operate at 150-220°C (302-428°F) and achieve 35 to 45% fuel-to-electricity efficiencies LHV.

Proton Exchange Membrane Fuel Cells (PEMFCs) operate at relatively low temperatures of 70-100°C (158-212°F), have high power density, can vary their output quickly to meet shifts in power demand, and are suited for applications where quick startup is required (e.g, transportation and power generation). The PEM is a thin fluorinated plastic sheet that allows hydrogen ions (protons) to pass through it. The membrane is coated on both sides with highly dispersed metal alloy particles (mostly platinum) that are active catalysts.

Molten Carbonate Fuel Cell (MCFC) technology has the potential to reach fuel-to-electricity efficiencies of 45 to 60% on a lower heating value basis (LHV). Operating temperatures for MCFCs are around 650° C (1,200°F), which allows total system thermal efficiencies up to 85% LHV in combined-cycle applications. MCFCs have been operated on hydrogen, carbon monoxide, natural gas, propane, landfill gas, marine diesel, and simulated coal gasification products.

Solid Oxide Fuel Cells (SOFCs) operate at temperatures up to 1,000°C (1,800°F), which further enhances combined-cycle performance. A solid oxide system usually uses a hard ceramic material instead of a liquid electrolyte. The solid-state ceramic construction enables the high temperatures, allows more flexibility in fuel choice, and contributes to stability and reliability. As with MCFCs, SOFCs are capable of fuel-to-electricity efficiencies of 45 to 60% LHV and total system thermal efficiencies up to 85% LHV in combined-cycle applications.

Technology Applications

Fuel cell systems can be sized for grid-connected applications or customer-sited applications in residential, commercial, and industrial facilities. Depending on the type of fuel cell (most likely SOFC and MCFC), useful heat can be captured and used in combined heat and power systems (CHP).

Premium power applications are an important niche market for fuel cells. Multiple fuel cells can be used to provide extremely high (more then six nines) reliability and high-quality power for critical loads. Data centers and sensitive manufacturing processes are ideal settings for fuel cells.

Fuel cells also can provide power for vehicles and portable power. PEMFCs are a leading candidate for powering the next generation of vehicles. The military is interested in the high efficiency, low-noise, small-footprint portable power.

Current Status

Fuel cells are still too expensive to compete in widespread domestic and international markets without significant subsidies.

PAFC – More than 170 PAFC systems are in service worldwide, with those installed by ONSI having surpassed 2 million total operating hours with excellent operational characteristics and high availability.

Economic Specifications of the PAFC (200 kW)

Expense	Description	Cost
Capital Cost	1 complete PAFC power plant	$850,000
Installation	Electrical, plumbing, and foundation	$40,000
Operation	Natural gas costs	$5.35/MMcf
Minor Maintenance	Service events, semi-annual and annual maintenance	$20,000/yr
Major Overhaul	Replacement of the cell stack	$320,000/5 yrs

Source: Energetics, *Distributed Energy Technology Simulator: Phosphoric Acid Fuel Cell Validation*, May 2001.

PEMFC – Ballard's first 250 kW commercial unit is under test. PEM systems up to 200 kW are also operating in several hydrogen-powered buses. Most units are small (<10 kW). PEMFCs currently cost several thousand dollars per kW.

SOFC – A small, 25 kW natural gas tubular SOFC systems has accumulated more than 70,000 hours of operations, displaying all the essential systems parameters needed to proceed to commercial configurations. Both 5 kW and 250 kW models are in demonstration.

MCFC – 50 kW and 2 MW systems have been field-tested. Commercial offerings in the 250 kW-2 MW range are under development.

Some fuel cell developers include:

- Avista Laboratories
- Ball Aerospace and Technologies Corp.
- Ballard Power Systems, Inc
- BCS Technology, Inc.
- Ceramatec
- DCH Technology, Inc
- FuelCell Energy
- H Power
- IdaTech
- M-C Power
- ONSI Corporation (IFC/United Technologies)
- Plug Power, LLC
- Proton Energy Systems
- Siemens Westinghouse Power Corporation

Fuel Cell Type	Electrolyte	Operating Temp (°C)	Electrical Efficiency (% LHV)	Commercial Availability	Typical Unit Size Range	Start-up time (hours)
AFC	KOH	60-250		1960s		
PEMFC	Nafion	70-100	35-45	2000-2001	5-250 kW	< 0.1
PAFC	Phosphoric Acid	150-220	35-45	1993	200 kW	1-4
MCFC	Lithium, potassium, carbonate salt	600-650	45-60	Post 2003	250 kW-2 MW	5-10
SOFC	Yttrium & zirconium oxides	800-1000	45-60	Post 2003	5-250 kW	5-10

Sources: Anne Marie Borbely and Jan F. Kreider. *Distributed Generation: The Power Paradigm for the New Millennium*, CRC Press, 2001, and Arthur D. Little, Distributed Generation Primer: Building the Factual Foundation (multi-client study), February 2000

Technology History

In 1839, William Grove, a British jurist and amateur physicist, first discovered the principle of the fuel cell. Grove utilized four large cells, each containing hydrogen and oxygen, to produce electric power which was then used to split the water in the smaller upper cell into hydrogen and oxygen.

In the 1960s, alkaline fuel cells were developed for space applications that required strict environmental and efficiency performance. The successful demonstration of the fuel cells in space led to their serious consideration for terrestrial applications in the 1970s.

In the early 1970s, DuPont introduced the Nafion® membrane, which has traditionally become the electrolyte for PEMFC.

In 1993, ONSI introduced the first commercially available PAFC. Its collaborative agreement with the U.S. Department of Defense enabled more than 100 PAFCs to be installed and operated at military installations.

The emergence of new fuel cell types (SOFC, MCFC) in the past decade has led to a tremendous expansion of potential products and applications for fuel cells.

Technology Future

According to the Business Communications Company, the market for fuel cells was about $218 million in 2000, will rise to $2.4 billion by 2004, and will reach $7 billion by 2009.

Fuel cells are being developed for stationary power generation through a partnership of the U.S DOE and the private sector.

Industry will introduce high-temperature natural gas-fueled MCFC and SOFC at $1,000 -$1,500 per kW that are capable of 60% efficiency, ultra-low emissions, and 40,000 hour stack life.

DOE is also working with industry to test and validate the PEM technology at the 1–kW level and to transfer technology to the Department of Defense. Other efforts include raising the operating temperature of the PEM fuel cell for building, cooling, heating, and power applications and improve reformer technologies to extract hydrogen from a variety of fuels, including natural gas, propane, and methanol.

Fuel Cells

Technology Performance

Source: Arthur D. Little (ADL) estimates, survey of equipment manufacturers.

Only industrial applications; table does not address residential/commercial-scale fuel cells.

		2000 Characteristics						**2005 Characteristics**					
		Installed Cost ($/kW)		Non-Fuel O&M (cents/kWh)		Electrical Efficiency (LHV)		Installed Cost ($/kW)		Non-Fuel O&M (cents/kWh)		Electrical Efficiency (LHV)	
Technology	Size Range (kW)	Low	High	Low	High	High	Low	Low	High	Low	High	High	Low
Low Temperature Fuel Cell (PEM)	200-250	2,000	3,000	1.5	2.0	40%	30%	1,000	2,000	1.0	1.8	43%	33%
High Temperature Fuel Cell (SOFC & MCFC)	250-1,000	NA						1,500	2,000	1.0	2.0	55%	45%

Source: Energetics, *Distributed Energy Technology Simulator: PAFC Validation,* May 2001.

	Size (kW)	Capital Cost	Installation (Site Preparation)	Operation Costs (Natural Gas)	Minor Maintenance	Major Overhaul
Installation of a commercially available PAFC	200	$850,000	$40,000	$5.35/MMcf	$20,000/yr	$320,000/5 yrs

Technology Performance

There have been more than 25 fuel cell demonstrations funded by the private sector, the government, or a cofunded partnership of both. The objectives for most have been to validate a specific technology advance or application, and most of these demonstrations have been funded by the Office of Fossil Energy.

This is a listing of the demonstrations that have taken place between 1990 and today that have been published. All of the demonstrations were deemed a success, even if the testing had to end before its scheduled completion point. All of the manufacturers claimed they learned a great deal from each test. All the OPT-funded demonstrations were used to prove new higher performance-based technology either without lower catalyst levels, metal separator plates, carbon paper in lieu of machined carbon plates, or new membrane materials. Only the Plug Power fuel cell tested for the Remote Power Project failed, due to an electrical fire.

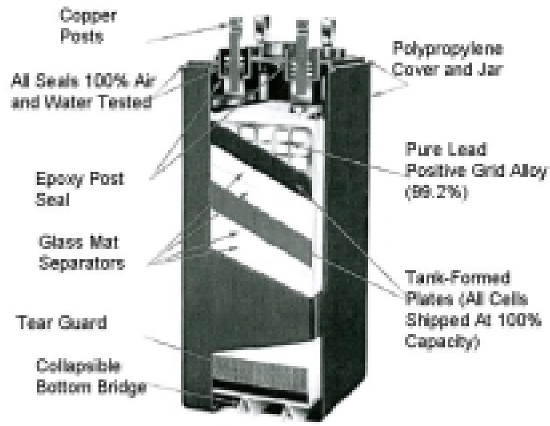
Fuel Cell Type	**Company**	**Objective**
Phosphoric Acid Fuel Cell	UT Fuel Cells (IFC)/FE	12.5 kW prototype using a new membrane assembly. (60 units) 40 kW power plant (46 units) 100 kW prototype for Georgetown Bus. (2 units) Methanol 200 kW first manufacturing prototype for PC25 (4 units) including natural gas reformer
Phosphoric Acid Fuel Cell	IFC/OPT	200 kW hydrogen version of PC 25 without a reformer, lower cost assembly
Solid Oxide	Westinghouse/FE	2 MW SOFC at Toshiba for fuels and tubular geometry testing 100 kW plannar unit to test seals, Netherlands 250 kW hybrid(57/50) w/turbine SoCal Ed 250 kW tubular SOFC combined heat and power, Ontario Power
Molten Carbonate	Fuel Cell Energy/FE	250 kW 8,800 hours Danbury Ct. first precommercial prototype 3 MW four years to build, Lexington Clean Coal Project 2 MW San Diego failed early
Proton Exchange Membrane	Plug Power/OTT Plug Power/OPT	10 kW prototype for vehicles 50 kW unsuccessful 25 kW prototype for Alaska, integrated with diesel reformer 50 kW prototype for Las Vegas refueling station, integrated with natural gas reformer

Proton Exchange Membrane	IFC/OTT	10 kW prototype sent to LANL for evaluation 50 kW prototype sent to GM for evaluation, reduced Pt catalyst 75 kW prototype installed in Hundai SUV, prototype for all transportation devices
Proton Exchange Membrane	Schatz Energy Center/OPT	(3) 5 kW Personal Utility Vehicles, (1) 15 kW Neighborhood Electric Vehicle Palm Desert each incorporated different levels of Pt catalyst, different membranes, all hydrogen fueled 1.3 kW Portable Power Unit
Proton Exchange Membrane	Enable/OPT	(3) 100 W Portable Power Units to demonstrate radial design (2) 1.5 kW Portable Power Units incorporating the LANL adiabatic fuel cell design (1) 1 kW "air breather" design for wheelchair
Proton Exchange Membrane	Ballard: no DOE funds	(6) 250 kW 40 foot passenger buses, hydrogen fueled: 3 Chicago, 2 Vancouver, 1 Palm Desert (1) 100 kW powerplant for Ford "Think" car (1) 250 kW stationary powerplant new manufacturing design
Proton Exchange Membrane	Nuvera/OPT	3 kW powerplant using metal separator plate technology for Alaska evaluated by SNL and University of Alaska
Proton Exchange Membrane	Coleman Powermate/Ballard no DOE funds	(3) 1.3 kW precommercial prototype UPS systems, metal hydride storage, under evaluation at United Laboratories for rating
Proton Exchange Membrane	Reliant Energy	7.5 kW precommercial prototype of radial stack geometry with conductive plastic separator plates
Alkaline	Zetec	25 kW precommercial prototype to demonstrate regenerative carbon dioxide scrubber
Alkaline	Hamilton Standard/IFC	(100) 12.5 kW commercial units for NASA
Alkaline	Union Carbide	(2) 50 kW fuel cells for GM van and car

Batteries

Technology Description

Batteries are likely the most widely known type of energy storage. They all store and release electricity through electrochemical processes and come in a variety of shapes and sizes. Some are small enough to fit on a computer circuit board while others are large enough to power a submarine. Some batteries are used several times everyday while others may sit idle for 10 or 20 years before they are ever used. Obviously for such a diversity of uses, a variety of battery types are necessary. But all of them work from the same basic principles.



System Concepts

Battery electrode plates, typically consisting of chemically reactive materials, are placed in an electrolyte, which facilitates the transfer of ions in the battery. The negative electrode gives up electrons during the discharge cycle. This flow of electrons creates electricity that is supplied to any load connected to the battery. The electrons are then transported to the positive electrode. This process is reversed during charging. Batteries store and deliver direct current (DC) electricity. Thus power conversion equipment is required to connect a battery to the alternating current (AC) electric grid.

Representative Technologies

The most mature battery systems are based on lead acid technology. There are two major kinds of lead acid batteries: flooded lead acid batteries and valve-regulated-lead-acid (VRLA) batteries.

There are several rechargeable, advanced batteries under development for stationary and mobile applications, including lithium-ion, lithium polymer, nickel metal hydride, zinc-air, zinc-bromine, sodium sulfur, and sodium bromide. These advanced batteries offer potential advantages over lead acid batteries in terms of cost, energy density, footprint, lifetime, operating characteristics reduced maintenance, and improved performance.

Technology Applications

Lead acid batteries are the most common energy storage technology for stationary and mobile applications. They offer maximum efficiency and reliability for the widest variety of stationary applications: telecommunications, utility switchgear and control, uninterruptible power supplies (UPS), photovoltaic, and nuclear power plants. They provide instantaneous discharge for a few seconds or a few hours.

Installations can be any size. The largest system to date is 20 MW. Lead acid batteries provide power quality, reliability, peak shaving, spinning reserve, and other ancillary services. The disadvantages of the flooded lead-acid battery include the need for periodic addition of water, and the need for adequate ventilation since the batteries can give off hydrogen gas when charging.

VRLA batteries are sealed batteries fitted with pressure release valves. They have been called low-maintenance batteries since they do not require periodic adding of water. They can be stacked horizontally as well as vertically, resulting in a smaller footprint than flooded lead acid batteries. Disadvantages include higher cost and increased sensitivity to the charging cycle used. High temperature results in reduced battery life and performance.

Several advanced "flow batteries" are under development. The zinc-bromine battery consists of a zinc positive electrode and a bromine negative electrode separated by a microporous separator. An aqueous solution of zinc/bromide is circulated through the two compartments of the cell from two separate reservoirs. Zinc-bromine batteries are currently being demonstrated in a number of hybrid installations, with microturbines and diesel generators. Sodium bromide/sodium bromine batteries are similar to zinc-bromine batteries in function and are under development for large-scale, utility applications. The advantages of flow battery technologies are low cost, modularity, scalability, transportability, low weight, flexible operation, and all components are easily recyclable. Their major disadvantages are a relatively low cycle efficiency.

Other advanced batteries include the lithium-ion, lithium-polymer, and sodium sulfur batteries. The advantages of lithium batteries include their high specific energy (four times that of lead-acid batteries) and charge retention. Sodium sulfur batteries operate at high temperature and are being tested for utility load leveling applications.

Current Status

Energy storage systems for large-scale power quality applications (~10 MW) are economically viable now with sales from one manufacturer doubling from 2000 to 2001.

Lead-acid battery annual sales have tripled between 1993 and 2000. The relative importance of battery sales for switchgear and UPS applications shrunk during this period from 45% to 26% of annual sales by 2000. VRLA and flooded battery sales were 534 and 171 million dollars, respectively, in 2000.

Recently, lead-acid battery manufacturers have seen sales drop with the collapse of the telecommunications bubble in 2001. They saw significant growth in sales in 2000, due to the demand from communications firms, and invested in production and marketing in anticipation of further growth. Many manufacturers have been subject to mergers and acquisitions. A few dozen manufacturers in the U.S. and abroad still make batteries.

Government and private industry are currently developing a variety of advanced batteries for transportation and defense applications: lithium-ion, lithium polymer, nickel metal hydride, sodium metal chloride, sodium sulfur, and zinc bromine.

Rechargeable lithium batteries already have been introduced in the market for consumer electronics and other portable equipment.

There are two demonstration sites of ZBB's Zinc Bromine batteries in Michigan and two additional ones in Australia.

Representative Current Manufacturers

Flooded	VRLA	Nickel Cadmium, Lithium Ion	Zinc Bromine
East Penn Exide Rolls Trojan	Hawker GNB Panasonic Yuasa	SAFT Sanyo Panasonic	Medentia Powercell ZBB

Technology History

Most historians date the invention of batteries to about 1800 when experiments by Alessandro Volta resulted in the generation of electrical current from chemical reactions between dissimilar metals.

Secondary batteries date back to 1860 when Raymond Gaston Planté invented the lead-acid battery. His cell used two thin lead plates separated by rubber sheets. He rolled the combination up and immersed it in a dilute sulfuric acid solution. Initial capacity was extremely limited since the positive plate had little active material available for reaction.

Others developed batteries using a paste of lead oxides for the positive plate active materials. This allowed much quicker formation and better plate efficiency than the solid Planté plate. Although the rudiments of the flooded lead-acid battery date back to the 1880s, there has been a continuing stream of

improvements in the materials of construction and the manufacturing and formation processes.
Since many of the problems with flooded lead-acid batteries involved electrolyte leakage, many attempts have been made to eliminate free acid in the battery. German researchers developed the gelled-electrolyte lead-acid battery (a type of VRLA) in the early 1960s. Working from a different approach, Gates Energy Products developed a spiral-wound VRLA cell, which represents the state of the art today.

Technology Future

Lead-acid batteries provide the best long-term power in terms of cycles and float life and, as a result, will likely remain a strong technology in the future.
Energy storage and battery systems in particular will play a significant role in the Distributed Energy Resource environment of the future. Local energy management and reliability are emerging as important economic incentives for companies.
A contraction in sales of lead-acid batteries that began in 2001 was expected to continue over the next few years until 9/11 occurred. Military demand for batteries may drastically alter the forecast for battery sales.
Battery manufacturers are working on incremental improvements in energy and power density.
The battery industry is trying to improve manufacturing practices and build more batteries at lower costs to stay competitive. Gains in development of batteries for mobile applications will likely crossover to the stationary market.
Zinc Bromine batteries are expected to be commercialized in 2003 with a target cost of $400/kWh.
A 10 MW-120 MWh sodium bromide system is under construction by the Tennessee Valley Authority
A 40 MW nickel cadmium system is being built for transmission line support and stabilization in Alaska.

Batteries

Market Data

Recent Battery Sales

Source: Battery Council International, Annual Sales Summary, October 2001.

	1993	2000	Growth
Flooded Batteries (Million $)	156.9	533.5	340%
VRLA Batteries (Million $)	79.6	170.6	214%
Total Lead-Acid Batteries (Million $)	236.5	704.1	298%

Percent Communications	58%	69%
Percent Switchgear/UPS	45%	26%

Market Predictions

Source: Sandia National Laboratories, Battery Energy Storage Market Feasibility Study, September 1997.

Year	MW	($ Million)
2000	496	372
2005	805	443
2010	965	434

Technology Performance

Grid-Connected Energy Storage Technologies Costs and Efficiencies

Source: Sandia National Laboratories, Characteristics and Technologies for Long- vs. Short-Term Energy Storage, March 2000.

Energy Storage System	Energy Related Cost ($/kWh)	Power Related Cost ($/kW)	Balance of Plant ($/kWh)	Discharge Efficiency
Lead-acid Batteries				
low	175	200	50	0.85
average	225	250	50	0.85
high	250	300	50	0.85
Power Quality Batteries	100	250	40	0.85
Advanced Batteries	245	300	40	0.7

Technology Performance

Off-Grid Storage Applications, Their Requirements, and Potential Markets to 2010 According to Boeing

Source: Sandia National Laboratories, Energy Storage Systems Program Report for FY99, June 2000.

Application	Single Home: Developing Community	Developing Community: No Industry	Developing Community: Light Industry	Developing Community: Moderate Industry	Advanced Community or Military Base
Storage System Attributes					
Power (kW)	0.5	8	40	400	1 MW
Energy (kWh)	3	45	240	3,600	1.5 MWh
Power					
Base (kW)	0.5	5	10	100	100
Peak (kW)		< 8	< 40	< 400	< 1000
Discharge Duration	5 to 72 hrs	5 to 72 hrs	5 to 24 hrs	5 to 24 hrs	0.5 to 1 hr
Total Projected Number of Systems	47 Million	137,000	40,000	84,000	131,000
Fraction of Market Captured by Storage	> 50	> 50	~ 30	~ 10	< 5
Total Number of Storage Systems to Capture Market Share	24 Million	69,000	12,000	8,000	< 7,000

Technology Performance

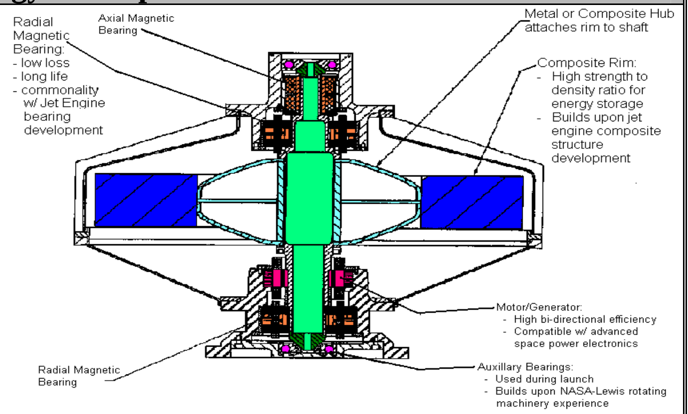
Advanced Batteries Characteristics Source: DOE Energy Storage Systems Program Annual Peer Review FY01, Boulder City Battery Energy Storage, November 2001.

Energy Storage System	Sodium Sulfur	Vanadium Redox	Zinc Bromine
Field Experience	Over 30 Projects, 25 kW to 6 MW, Largest 48 MW	Several Projects 100kW to 3 MW (pulse power), Largest 1.15 MWh	Several Projects, 50 kW to 250 kW, Largest 400 kWh
Production Capacity	160 MWh/yr	30 MWh/yr	40 to 70 MWh/yr
Actual Production	50 MWh/yr	10 MWh/yr	4.5 MWh/yr
Life	15 yrs	7 to 15 yrs	10 to 20 yrs
Efficiency	72%	70to 80 %	65 to 70%
O&M Costs	$32.5k/yr	$50k/yr	$30 to $150k/yr

Advanced Energy Storage

Technology Description

The U.S. electric utility industry has been facing new challenges with deregulation and limitations on installing new transmission and distribution equipment. Advanced storage technologies under active development, in addition to advanced batteries, include processes that are mechanical (flywheels, pneumatic storage) and purely electrical (supercapacitors, super-conducting magnetic storage), and compressed air energy storage. These advanced energy storage solutions will help achieve more reliable and low-cost electricity storage.



Flywheel Cutaway

System Concepts

Flywheels (Low-Speed and High-Speed)

Flywheels store kinetic energy in a rotating mass. The amount of stored energy is dependent on the speed, mass, and configuration of the flywheel. They have been used as short-term energy storage devices for propulsion applications such as engines for large road vehicles. Today, flywheel energy storage systems are usually categorized as either low-speed or high-speed. High-speed wheels are made of high-strength, low-density composite materials, making these systems considerably more compact than those employing lower-speed metallic wheels. However, the low-speed systems are still considerably less expensive per kWh.

Supercapacitors

Supercapacitors are also known as Electric Double Layer Capacitors, pseudocapacitors, or ultracapacitors. Charge is stored electrostatically in polarized liquid layers between an ionically conducting electrolyte and a conducting electrode. Though they are electrochemical devices, no chemical reactions occur in the energy storage mechanism. Since the rate of charge and discharge is determined solely by its physical properties, an ultracapacitor can release energy much faster (i.e., with more power) than a battery, which relies on slow chemical reactions. Ultracapacitors have 100 times the power density of conventional capacitors and 10 times the power density of ordinary batteries.

Compressed Air Energy Storage (CAES)

CAES systems work as follows: during off-peak hours, air is pumped into underground tanks and compressed using low-cost electricity at pressures up to 1,078 pounds per square inch. During peak times, the compressed air is released and heated using a small amount of natural gas. The heated air flows through a turbine generator, which produces electricity. In conventional gas-turbine power generation, the air that drives the turbine is compressed and heated using natural gas. In contrast, CAES technology needs less gas to produce power, because it uses air that already has been compressed and stored.

Superconducting Magnetic Energy Storage (SMES)

SMES systems store energy in the magnetic field created by the flow of direct current in a coil of superconducting material. SMES systems provide rapid response to either charge or discharge, and their available energy is independent of their discharge rate. SMES systems have a high cycle life and, as a result, are suitable for applications that require constant, full cycling and a continuous mode of operation. Micro-SMES devices in the range of 1 to 10 MW are available commercially for power-quality applications.

Representative Technologies

- While the system concepts section addressed energy storage components exclusively, all advanced storage systems require power conditioning and balance of plant components.
- For vehicle applications, flywheels, CAES, and ultracapacitors are under development.
- A dozen companies are actively developing flywheels – steel, low-speed flywheels, are commercially available now; composite, high-speed flywheels are rapidly approaching commercialization.
- Pneumatic storage (CAES) is feasible for energy storage on the order of 100's MWh.
- Prototype ultracapacitors have recently become commercially available.

Technology Applications

- Energy available in SMES is independent of its discharge rating, which makes it very attractive for high power and short time burst applications such as power quality.
- SMES are also useful in transmission enhancement as they can provide line stability, voltage and frequency regulation, as well as phase angle control.
- Flywheels are primarily used in transportation, defense, and power-quality applications.
- Load management is another area where advanced energy storage systems are used (e.g., CAES). Energy stored during off-peak hours is discharged at peak hours, achieving savings in peak energy, demand charges, and a more uniform load.
- Load management also enables the deferral of equipment upgrades required to meet an expanding load base, which typically only overloads equipment for a few hours a day.
- Ultracapacitors are used in consumer electronics, power quality, transportation, and defense and have potential applications in combination with distributed generation equipment for following rapid load changes.

Current Status

- Utilities require high reliability, and per-kilowatt costs less than or equal to those of new power generation ($400–$600/kW). Compressed gas energy storage can cost as little as $1–$5/kWh. SMES has targets of $150/kW and $275/kWh. Vehicles require storage costs of $300 to $1000/kWh to achieve significant market penetration. The major hurdle for all storage technologies is cost reduction.
- Ultracapacitor development needs improved energy density from the current 1.9 W-h/kg for light-duty hybrid vehicles.
- Low-speed (7000-9000 rpm) steel flywheels are commercially available for power quality and UPS applications.
- There is one 110-MW CAES facility operated by an electric co-op in Alabama.
- Six SMES units have been installed in Wisconsin to stabilize a ring transmission system.

Representative Current Manufacturers

Flywheels	Supercapacitors	CAES	SMES
Active Power American Flywheel Systems Pillar	Nanolab Cooper Maxwell NEC	Ingersoll Rand ABB Dresser-Rand Alstrom	American Superconductor

Technology Future
• Developments in the vehicular systems most likely will crossover into the stationary market. • High-temperature (liquid-nitrogen temperatures) superconductors that are manufacturable and can carry high currents could reduce both capital and operating costs for SMES. • High-speed flywheels need further development of fail-safe designs and/or lightweight containment. Magnetic bearings will reduce parasitic loads and make flywheels attractive for small uninterruptible power supplies and small energy management applications. • Much of the R&D in advanced energy storage is being pursued outside the United States, in Europe, and Japan. U.S. government research funds have been very low, relative to industry investments. One exception has been the Defense Advanced Research Programs Agency, with its flywheel containment development effort with U.S. flywheel manufacturers, funded at $2 million annually. The total DOE Energy Storage Program budget hovers in the 4-6 M$ range during the past 10 years.

Advanced Energy Storage

Market Data

Market Predictions

Source: Sandia National Laboratories, Cost Analysis of Energy Storage Systems for Electric Utility Applications, February 1997.

Energy Storage System	Present Cost	Projected Cost Reduction
SMES	$54,000/MJ	5-10%
Flywheels	$200/kWh	443

Technology Performance

Energy Storage Costs and Efficiencies

Source: Sandia National Laboratories, Characteristics and Technologies for Long- vs. Short-Term Energy Storage, March 2000.

Energy Storage System	Energy Related Cost ($/kWh)	Power Related Cost ($/kW)	Balance of Plant ($/kWh)	Discharge Efficiency
Micro-SMES	72,000	300	10,000	0.95
Mid-SMES	2,000	300	1,500	0.95
SMES	500	300	100	0.95
Flywheels (high-speed)	25,000	350	1,000	0.93
Flywheels (low-speed)	300	280	80	0.9
Ultracapacitors	82,000	300	10,000	0.95
CAES	3	425	50	0.79

Technology Performance

Energy Storage Technology Profiles

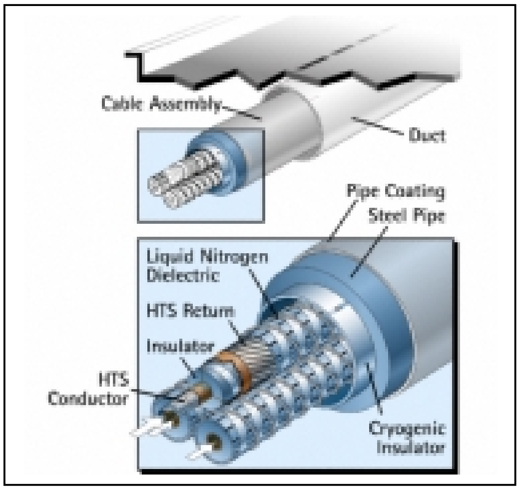
Source: DOE/EPRI, Renewable Energy Technology Characterizations, December 1997, Appendix A.

Technology	Installed U.S. Total	Facility Size Range	Potential/Actual Applications
Flywheels	1-2 demo facilities, no commercial sites. In 2002, steel flywheels with rotational speeds of 7000-9000 rpm are commercially available for power quality and UPS applications.	kW scale	Electricity (Power Quality) Transportation, Defense
SMES	5 facilities with approx. 30 MW in 5 states	From 1-10 MW (micro-SMES) to 10-100 MW	Electricity (T&D, Power Quality)
Ultracapacitors	Millions of units for standby power; 1 defense unit	7-10 W commercial 10-20 kW prototype	Transportation Defense Consumer Electronics Electricity (Power Quality)
CAES	110 MW in Alabama	25 MW to 350 MW	Electricity (Peak-shaving, Spinning Reserve, T&D)

Superconducting Power Technology

Technology Description

Superconducting power technology refers to electric power equipment and devices that use superconducting wires and coils. High Temperature Superconductivity (HTS) enables electricity generation, delivery and end use without the resistance losses encountered in conventional wires made from copper or aluminum. HTS wires have the potential to carry 100 times the current without the resistance losses of comparable diameter copper wires. HTS power equipment, such as motors, generators, and transformers, has the potential to be half the size of conventional alternatives with the same power rating and only half the energy losses.



Source: American Superconductor

System Concepts

- HTS systems will be smaller, more efficient, and carry more power than a similarly rated conventional system.
- HTS systems will help the transmission and distribution system by allowing for greater power transfer capability, increased flexibility, and increased power reliability.

Representative Technologies

Transmission Cables	Current Limiters
Motors	Transformers
Generators	Flywheel Electricity Systems

Technology Applications

- Superconducting technology will modernize the electric grid and infrastructure, resulting in greater flexibility, efficiency and cost effectiveness.
- Wire and Coils have reached a sufficient level of development to allow for their introduction into prototype applications of HTS systems such as motors, generators, transmission cables, current limiters and transformers.
- Motors rated greater than 1,000 hp will primarily be used for pump and fan drives for utility and industrial markets.
- Current Controllers will perform as a fast sub-cycle breaker when installed at strategic locations in the transmission and distribution system.
- Flywheel electricity systems can be applied to increase electric utility efficiency in two areas—electric load leveling and uninterruptible power systems (UPS) applications.
- Transformers are environmentally friendly and oil-free, making them particularly useful where transformers previously could not be sited, such as in high density urban areas or inside buildings.
- Reciprocating Magnetic Separators can be used in the industrial processing of ores, waste solids, and waste gases, as well as performing isotope separations and water treatment.

Current Status

- Much of the research and development in HTS is focused on wire and system development and prototype system design and deployment.
- There are 18 manufacturers, 8 National Laboratories, 6 utilities, and 17 universities participating in the U.S. Department of Energy Superconductivity Program alone. The list of manufacturers includes:

3M	ABB
American Superconductor	Pirelli Cables North America
IGC SuperPower	Waukesha Electric Systems
Southwire Company	

- Prototype power transmission cables have been developed and are being tested by two teams led by Pirelli Cable Company and Southwire Company respectively.
- A 1,000 horsepower prototype motor was produced and tested by Rockwell Automation/Reliance Electric Company. The results of these tests are being used to design a 5,000 hp motor.
- A team led by General Electric has developed a design for a 100 MW generator.
- A 15 kV Current Controller was tested at a Southern California Edison substation in July 1999.
- The design of a 3 kW/10 kWh flywheel system has been completed. The superconducting bearings, motor/generator, and control system have been constructed and are undergoing extensive testing. A rotor construction is underway.
- The design of the reciprocating magnetic separator has been finalized, and components for the system have been procured and assembled. The test site has been prepared, and cryogenic testing has begun.

Technology History

- In 1911, after technology allowed liquid helium to be produced, Dutch Physicist Heike Kammerlingh Onnes found that at 4.2 K, the electrical resistance of mercury decreased to almost zero. This marked the first discovery of superconducting materials.
- Until 1986, superconductivity applications were highly limited due to the high cost of cooling to such low temperatures, which resulted in costs higher than the benefits of using the new technology.
- In 1986, two IBM scientists, J. George Bednorz and Karl Müller achieved superconductivity on lanthanum copper oxides doped with barium or strontium at temperatures as high as 38 K.
- In 1987, the compound $Y_1Ba_2Cu_3O_7$ (YBCO) was given considerable attention as it possessed the highest critical temperature at that time, at 93 K. In the following years, other copper oxide variations were found, such as bismuth lead strontium calcium copper oxide (110 K), and thallium barium calcium copper oxide (125 K).
- In 1990, the first (dc) HTS motor was demonstrated.
- In 1992 a 1-meter long HTS cable was demonstrated.
- By 1996, a 200-horsepower HTS motor was tested and exceeded its design goals by 60%.

Technology Future

Year of 50% Market Penetration

Motors	Transformers	Generators	Underground Cable
2016	2015	2021	2013

Source: ORNL/Sub/4500006921, 2000 Edition - High Temperature Superconductivity: The Products and Their Benefits.

- Low-cost, high-performance YBCO Coated Conductors will be available in 2005 in kilometer lengths.
- The present cost of HTS wire is $300/kA-m. By 2005, for applications in liquid nitrogen, the wire cost will be less than $50/kA-m and for applications requiring cooling to temperatures of 20-60 K the cost will be less than $30/kA-m.
- By 2010, the cost-performance ratio will have improved by at least a factor of four. The cost target is $10/kA-m.

Superconducting Power Technology

Market Data

Projected Market for HTS devices (Thousands of Dollars)	Source: U.S. Department of Energy, September 2001, Analysis of Future Markets for High Temperature Superconductors, Draft.							
Year	**2011**	**2013**	**2015**	**2017**	**2019**	**2021**	**2023**	**2025**
Motors	228	956	4,025	15,399	50,968	108,429	148,770	164,072
Transformers	0	0	243	1,451	9,353	56,081	222,277	390,964
Generators	6,926	24,710	83,634	227,535	445,693	592,904	656,499	675,656
Cables	4,117	14,405	48,335	135,001	318,844	488,783	570,326	586,284
Total	11,270	40,071	136,236	379,386	824,857	1,246,196	1,597,872	1,816,975

Underground Power Cables: Market Penetration and Benefits Case 1	Source: ORNL/Sub/4500006921, 2000 Edition - High Temperature Superconductivity: The Products and Their Benefits								
	2004	**2006**	**2008**	**2010**	**2012**	**2014**	**2016**	**2018**	**2020**
% Market	0	6.7	15	27	40	56	69	77	80
Miles Sold this Year	0	13.89	32.68	61.77	96.19	141.47	183.15	214.73	234.35
Total Miles Installed	0	20.76	74.69	183.34	356.96	616.75	963.05	1,379	1,839
Total Annual Savings (10^6 $)	0	0.165	0.582	1.4	2.68	4.56	6.98	9.82	12.86

Underground Power Cables: Market Penetration and Benefits

Case 2

Source: ORNL/Sub/4500006921, 2000 Edition - High Temperature Superconductivity: The Products and Their Benefits

	2004	2006	2008	2010	2012	2014	2016	2018	2020
% Market	0	6.7	15	27	40	56	69	77	80
Miles Sold this Year	0	12.33	28.39	52.56	80.07	115.2	145.98	167.53	178.98
Total Miles Installed	0	18.42	65.49	158.36	303.55	516.13	793.6	1120	1473
Total Annual Savings (10^6 $)	0	0.145	0.506	1.2	2.261	3.778	5.698	7.897	10.2

The first case is based on electrical generation and equipment market growth averaging 2.5% per year through 2020. This number was chosen based on historic figures from 1990-1998 and the assumption that a strong economy will continue this kind of growth. Case 2 follows present EIA projections of 1.4% growth, with somewhat more conservative results.

Technology Performance

HTS Energy Savings (GWh)

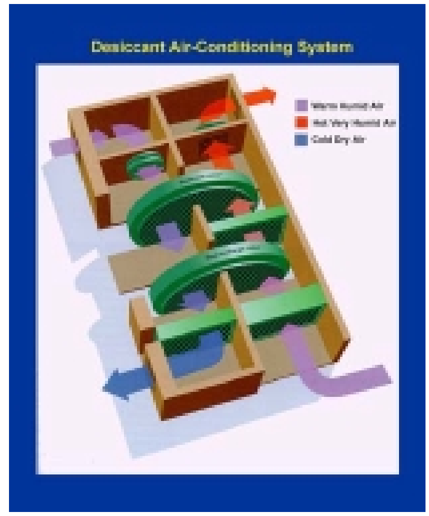
Source: U.S. Department of Energy, September 2001, Analysis of Future Markets for High Temperature Superconductors, Draft.

Year	2009	2011	2013	2015	2017	2019	2021	2023	2025
Motors	0	0	1	4	15	57	154	300	468
Transformers	0	0	0	0	2	15	94	449	1,194
Generators	2	11	44	171	556	1,417	2,699	4,196	5,785
Cables	1	3	13	55	196	598	1,336	2,289	3,326
Total	3	14	58	231	769	2,086	4,283	7,235	10,774

Thermally Activated Technologies

Technology Description

Thermally Activated Technologies (TATs), such as heat pumps, absorption chillers, and desiccant units, provide onsite space conditioning and water heating,which greatly reduce the electric load of a residential or commercial facility. These technologies can greatly contribute to system reliability.



System Concepts

TATs may be powered by natural gas, fuel oil, propane, or biogas, avoiding substantial energy conversion losses associated with electric power transmission, distribution, and generation.

These technologies may use the waste heat from onsite power generation and provide total energy solutions for onsite cooling, heating, and power.

Representative Technologies

Thermally activated heat pumps can revolutionize the way residential and commercial buildings are heated and cooled. This technology enables highly efficient heat pump cycles to replace the best natural gas furnaces, reducing energy use as much as 50%. Heat pumps take in heat at a lower temperature and release it a higher one, with a reversing valve that allows the heat pump to provide space heating or cooling as necessary. In the heating mode, heat is taken from outside air when the refrigerant evaporates and is delivered to the building interior when it condenses. In the cooling mode, the function of the two heat-exchanger coils is reversed, so heat moves inside to outside.

Absorption chillers provide cooling to buildings by using heat. Unlike conventional electric chillers, which use mechanical energy in a vapor compression process to provide refrigeration, absorption chillers primarily use heat energy with limited mechanical energy for pumping. The chiller transfers thermal energy from the heat source to the heat sink through an absorbent fluid and a refrigerant. The chiller achieves its refrigerative effect by absorbing and then releasing water vapor into and out of a lithium bromide solution. In the process, heat is applied at the generator and water vapor is driven off to a condenser. The cooled water vapor then passes through an expansion valve, reducing the pressure. The low-pressure water vapor then enters an evaporator, where ambient heat is added from a load and the actual cooling takes place. The heated, low-pressure vapor returns to the absorber, where it recombines with lithium bromide and becomes a low-pressure liquid. This low-pressure solution is pumped to a higher pressure and into the generator to repeat the process.

Desiccant equipment is useful for mitigation of indoor air quality problems and for improved humidity control in buildings. The desiccant is usually formed in a wheel made up of lightweight honeycomb or corrugated material (see figure). Commercially available desiccants include silica gel, activated alumina, natural and synthetic zeolites, lithium chloride, and synthetic polymers. The wheel is rotated through supply air, usually from the outside, and the material naturally attracts the moisture from the air before it is routed to the building. The desiccant is then regenerated using thermal energy from natural gas, the sun, or waste heat.

Technology Applications
Thermally activated heat pumps are a new generation of advanced absorption cycle heat pumps that can efficiently condition residential and commercial space. Different heat pumps will be best suited for different applications. For example, the GAX heat pump is targeted for northern states because of its superior heating performance, and the Hi-Cool heat pump is being developed for southern states, where cooling is the priority. Absorption chillers can change a building's thermal and electric profile by shifting the cooling from an electric load to a thermal load. This shift can be very important for facilities with time of day electrical rates, high cooling season rates, and high demand charges. Facilities with high thermal loads, such as data centers, grocery stores, and casinos, are promising markets for absorption chillers. Desiccant technology can either supplement a conventional air-conditioning system or act as a standalone operation. A desiccant can remove moisture, odors, and pollutants for a healthier and more comfortable indoor environment. Facilities with stringent indoor air quality needs (schools, hospitals, grocery stores, hotels) have adapted desiccant technology. CHP applications are well suited for TATs. They offer a source of "free" fuel in the form of waste heat that can power heat pumps and absorption chillers, and regenerate desiccant units.
Current Status
Thermally activated heat pump technology can replace the best natural gas furnace and reduce energy use by as much as 50%, while also providing gas-fired technology. Desiccant technology may be used in pharmaceutical manufacturing to extend the shelf life of products; refrigerated warehouses to prevent water vapor from forming on the walls, floors, and ceilings; operating rooms to remove moisture form the air, keeping duct work and sterile surfaces dry; and hotels, to prevent buildup of mold and mildew. Companies that manufacture TAT equipment include: York International — Broad Trane — Air Technology Systems Munters Corporation — American Power Conversion Company Kathabar Systems — Goettl
Technology History
In the 1930s, the concept of dehumidifying air by scrubbing it with lithium chloride was introduced, paving the way for development of the first desiccant unit. Trane introduced the first mass-produced steam-fired double-effect LiBr/H_2O absorption chiller in 1970. In 1987, the National Appliance Energy Conversion Act instituted minimum efficiency standards for central air conditioners and heat pumps.
Technology Future
Expand the residential market of the second-generation Hi-Cool residential absorption heat pump technology to include markets in southern states; the targeted 30% improvement in cooling performance can only be achieved with major new advancements in absorption technology or with an engine-driven system. Work in parallel with the first-generation GAX effort to determine the most attractive second-generation Hi-Cool technology. Fabricate and test the 8-ton advanced cycle VX GAX ammonia/water heat pump. Fabricate and test the 3-ton complex compound heat pump and chiller. Develop, test, and market an advanced Double Condenser Coupled commercial chiller, which is expected to be 50% more efficient than conventional chillers. Assess new equipment designs and concepts for desiccants using diagnostic techniques, such as infrared thermal performance mapping and advanced tracer gas leak detection.